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SAND RESOURCES AND GEOLOGICAL CHARACTER OF LONG ISLAND SOUND.(U)
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Sand Resources and Geological Character of Long Island Sound

by

S. Jeffress Williams

TECHNICAL PAPER NO. 81-3

MAY 1981

U.S. ARMY, CORPS OF ENGINEERS
COASTAL ENGINEERING
RESEARCH CENTER
Kingman Building
Fort Belvoir, Va. 22060

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: TP-81-3	2. GOVT ACCESSION NO. AD-A104 082
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): SAND RESOURCES AND GEOLOGICAL CHARACTER OF LONG ISLAND SOUND	5. TYPE OF REPORT & PERIOD COVERED: Technical Paper
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): S. Jeffress Williams	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Department of the Army, Coastal Engineering Research Center (CEREN-GE), Kingman Building, Fort Belvoir, Virginia 22060	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: D31665
11. CONTROLLING OFFICE NAME AND ADDRESS: Department of the Army, Coastal Engineering Research Center, Kingman Building, Fort Belvoir, Virginia 22060	12. REPORT DATE: May 1981
	13. NUMBER OF PAGES: 65
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Beach nourishment	Sand and gravel resources
Geomorphology	Sediments
ICONS	Seismic reflection profiles
Long Island Sound	Shore restoration

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Long Island Sound, covering almost 3,400 square kilometers of the region between Long Island, New York, and the Connecticut mainland, was studied using 700 kilometers of high-resolution seismic profiles and 75 vibratory cores to determine the geologic character and Quaternary history and evolution of the Sound, as well as to assess the resource potential of sand and gravel in sea-floor deposits.

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The subbottom consists of igneous and metamorphic bedrock that crops out close to the Connecticut shore and slopes south to depths of −250 meters at the Long Island north shore. The bedrock surface under the Sound is highly irregular and exhibits relief on the order of ±30 meters. There are numerous buried river channels that generally trend north-south in the western Sound, and apparently project south under Long Island; a large east-west channel along the Long Island north shore that underlies eastern Long Island and Gardiners Bay, projects south to possibly join the Block Island Shelf channel. Many channels, deeply scoured by Pleistocene glaciers, project south from present-day rivers along the Connecticut shore. The deepest channel at −244 meters MSL underlies New Haven Harbor and trends southwest past a bedrock high at Stratford Shoal and then projects south under the Long Island mainland.

Cretaceous strata overlie the bedrock in isolated areas of the middle of the Sound and exhibit considerable surface relief due to erosion by multiple glacial advances. Pleistocene sediments consist of thick accumulations of very firm varvelike silts and clays filling and overlying the bedrock surface throughout much of the central Sound, as well as moderately to poorly sorted sands and gravels up to boulder size that were placed as discontinuous recessional moraine segments, glacial outwash heads, and fluvial deltas. The presence of these glacial depositional features on the seabed from the western end of the Sound to about the Connecticut River longitude is evidence for one or more readvances of the late Wisconsin glacier subsequent to deposition of the Harbor Hill Moraine rimming the Long Island north shore.

Holocene sediments consist primarily of organic sandy muds that are accumulating in low energy environments. The primary sources of these fine-grained materials are coastal erosion of glacial debris, riverine inputs, and landward transport of fines from adjacent Block Island Sound and the inner shelf.

Fourteen isolated shoal features have been identified as offering the highest potential as sources of beach-fill sand and construction aggregate. Based on available data, a conservative estimate is that 189 million cubic meters of sand and gravel is available in water depths not exceeding 20 meters if the latest dredging technology were used.

PREFACE

This report describes results of the Inner Continental Shelf Sediment and Structure (ICONS) study of Long Island. The primary objectives of the study were to locate and delineate offshore sand and gravel deposits suitable for beach nourishment and to provide information on the geologic character of Long Island Sound. The work was carried out under the coastal processes program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by S. Jeffress Williams, a CERC research geologist, under the general supervision of Dr. C.H. Everts, Chief, Engineering Geology Branch. As part of the research program of the Engineering Development Division, the ICONS study is under the general supervision of N. Parker, Chief of the Division. The fieldwork (involving coring and continuous seismic profiling) was accomplished under contract with Alpine Geophysical Associates, Inc.

Discussions with E.P. Meisburger (CERC) were helpful in preparation of the study; final manuscript reviews by E.P. Meisburger and Dr. C.H. Everts were appreciated.

Microfilm copy of all seismic data is stored at the National Solar and Terrestrial Geophysical Data Center (NSTGDC), Rockville, Maryland 20852. Cores collected during the field survey program are in custody of the University of Texas, Arlington, Texas 76010, under agreement with CERC. Requests for information relative to these items should be directed to NSTGDC or the University of Texas.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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FIGURES--Continued

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.
To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SAND RESOURCES AND GEOLOGICAL CHARACTER OF LONG ISLAND SOUND

by
S. Jeffress Williams

I. INTRODUCTION

1. Background.

Ocean beaches and dunes constitute a vital buffer zone between the sea and populated coastal areas, and also provide much-needed recreation areas for the public. The construction, improvement, and maintenance of beaches through the placement (nourishment) of sand on the shore is one of several protection methods. This technique has gained prominence in coastal engineering largely as a result of the successful program initiated at Santa Barbara, California, in 1938 (Hall, 1952).

Where a specified plan of improvement involves shore restoration and periodic nourishment, large volumes of sandfill may be needed. In recent years it has become increasingly difficult to obtain suitable sand from lagoonal or inland sources in sufficient quantities and at an economical cost for beach-fill purposes. This difficulty is due in part to increased land value, depletion of previously used nearby sources, and added cost of transporting sand from areas increasingly remote. Material composing the bottom and subbottom of estuaries, lagoons, and bays is often too fine grained and unsuitable for long-term protection. Regardless of the fill source, beach sediment seeks equilibrium with its environment. However, it is possible to estimate the amount of material that will be lost through sorting in the surf zone by a quantitative comparison of the placed material with the native material and therefore minimize losses through selection of the most suitable fill material (Krumbein and James, 1965; James, 1974; Hobson, 1977).

The problem of locating suitable sand supplies led the Corps of Engineers to a search for new unexploited deposits of sand. The search focused offshore with the intent to explore and inventory deposits suitable for future beach-fill requirements. This exploration program is conducted through the U.S. Army Coastal Engineering Research Center (CERC).

In 1964, a program was initiated to survey offshore regions of the Atlantic, Pacific, gulf, and Great Lakes coastal areas to delineate the character of sand deposits. Formerly called the Sand Inventory Program, it began with a survey off the New Jersey coast. Subsequent surveys have included the Inner Continental Shelf off Florida, Texas, New England, New York, Maryland, North Carolina, Delaware, Virginia, California, and Lakes Michigan and Erie. Recognizing a broader application to the CERC mission of information collected in conduct of the research, the program was referred to as the Inner Continental Shelf Sediment and Structure (ICONS) program. The ICONS program was directed not only toward the mapping of sand deposits suitable for beach restoration but also the delineation of shelf structural characteristics, analysis of shelf history and sediment sources (Duane, et al., 1972; Pilkey and Field, 1972; Field, et al., 1979), determination of regional engineering properties of shelf sediments (Williams and Duane, 1972), and effects of ocean dumping (Williams, 1979).

An early study by the Corps of Engineers in evaluating techniques for transferring offshore sand to the beach is described by Mauriello (1967). This experiment at Sea Girt, New Jersey, involved dredging of 191,000 cubic meters of sand by the hopper dredge, *Goethals*, at a location 3.2 kilometers offshore from the beach segment to be restored. The loaded dredge, which had a pumpout capability, docked alongside an anchored barge and the sand was pumped ashore through a submerged pipeline.

At Redondo Beach, California, in 1967-68, the U.S. Army Engineer District, Los Angeles, contracted dredging of more than 1.1 million cubic meters of sand from offshore depths of 12 meters and transferring the sand to the beach. These operations, as well as others conducted in open-ocean environments in Long Island Sound and along the gulf and Atlantic coasts, have demonstrated the feasibility of using offshore marine and lake deposits for beach nourishment operations.

Along the Connecticut shore alone, about 32 kilometers of beaches have been filled and nourished from about 1940 to 1970 by using hydraulic dredges to pump material to the beaches from offshore source areas (McCabe, 1970). The projects were cooperative efforts between the Corps of Engineers, the State of Connecticut, and the individual towns along the shore. In some cases the fill sand was derived from navigation channel dredging, but more often it was obtained from borrow pits close to the project beaches.

2. Field and Laboratory Procedures.

The exploration phase of the ICONS program uses seismic reflection profiling supplemented by cores of the bottom sediment. Supporting data for the studies are obtained from National Ocean Survey (NOS) hydrographic smooth sheets and from literature sources. Planning, seismic reflection profiling, coring, positioning, and analysis of sediment obtained in the cores are detailed in Williams and Duane (1974). A brief description of these techniques follows:

a. Planning. Survey tracklines were laid out initially in grid or reconnaissance lines. A grid pattern (line spacing of about 4 to 5 kilometers) was used to cover areas where a more detailed development of bottom and subbottom conditions was desired.

Selection of core sites was based on a continuing review of the seismic profiles as they became available during the survey. This procedure allowed core-site selection based on the best information available; it also permitted the coring to be completed in one area before coring was started at another site.

b. Seismic Reflection Profiling. Seismic reflection profiling is a technique for delineating subbottom structures and bedding planes in sediments and rocks underlying water-covered areas. Continuous reflections are obtained by generating repetitive, high-energy sound pulses underwater near the water surface and recording "echoes" reflected from the bottom-water interface, and subbottom interfaces beween acoustically dissimilar materials. In general, compositional and physical properties which commonly differentiate sediments and rocks also produce acoustic contrasts. Thus, an acoustic profile is roughly comparable to a geologic cross section.

Seismic reflection surveys of marine areas are made by towing sound-generating sources and receiving instruments behind a survey vessel which follow predetermined survey tracklines. For continuous profiling, the sound source is fired at a rapid rate, and returning signals are amplified and fed to a recorder which graphically plots the two-way signal traveltime. Assuming a constant speed for sound in water and shelf sediments, a vertical depth scale can be constructed to the chart paper. Horizontal location is obtained by frequent (2-minute intervals) navigational fixes keyed to the chart record by an event marker.

General seismic profiling techniques are discussed in Moore and Palmer (1968) and American Association of Petroleum Geologists (1977).

Seismic reflection profiles for this study were made with an engineering "sparker" (Alpine Geophysical Associates, Inc., 1965). Two sound sources, one operated at 100 joules and the other at 200 joules, were fired alternately at a pulse rate of 4 per second during the survey. Returns from the sound sources were recorded by a dual-channel recorder which displayed the results on a single strip chart.

c. Coring Techniques. An Alpine Geophysical Associates, Inc. pneumatic, vibrating hammer-driven coring assembly was used to obtain cores from the survey area. The apparatus consists of a standard 5-meter-long core barrel, acrylic liner, and shoe and core catcher, with the driver element fastened to the upper end of the barrel. These are enclosed in a self-supporting frame which allows the assembly to rest on the bottom during coring, thus not influenced by limited motion of the support vessel in response to waves. Power is supplied to the vibrator from a deck-mounted air compressor by means of a flexible hoseline. After the core is driven and returned, the liner containing the cored material is removed and capped. Denser materials (compact sands; partially lithified rocks) are more difficult to penetrate than loose materials. Cohesive materials cause drag on the liner walls and give some distortion.

d. Navigation. Position location was determined during the survey by use of the Decca Navigator Mark 12 Receiver and Track Plotter which accurately located the vessel with respect to two onshore reference points. Navigation fixes were made at 2-minute intervals during all seismic reflection survey work and at each core position. Final plots of trackline and core location compiled from survey data were prepared at scales of 1:80,000.

e. Processing. Seismic records were analyzed to establish the principal bedding, erosional, constructional, and structural features in upper subbottom strata. After preliminary analysis, typical records were reduced to detailed cross-sectional profiles showing all reflective interfaces within several hundred feet of the bottom. Selected reflectors, considered significant because of their extent and relationship to the general structure and geology of the study area, were then mapped. If possible, the uppermost mapped reflector was correlated with core data to provide a measure of continuity between cores.

Cores were visually inspected and logged aboard ship. After delivery to CERC, the cores were sampled every foot by drilling through the liners and removing samples of representative material. After preliminary analysis, a number of representative cores were split to determine details of the bedding.

Cores were set up for splitting in a wooden trough. A circular powersaw mounted on a base which is designed to ride along the top of the trough was set to cut just through the liner. By making a cut in one direction and then reversing the saw base and making a second cut in the opposite direction, a 120° segment of the liner was cut. The sediment above the cut line was then removed with a spatula, the core logged, sampled, and photographed.

Samples from cores were examined under a binocular microscope, and described in terms of gross lithology, mineralogy, and the type and abundance of skeletal fragments of organisms. Petrographic analysis through transmitted-light microscopy was performed on certain core samples that coincided with prominent acoustic reflectors to further delineate their nature and origin of associated sediments.

Data processing included analysis of all seismic reflection records and reduction to line profile drawings. Cores were logged and sampled to provide sediment representative of each sediment facies penetrated. The samples were visually described and size analysis was made by means of a fall velocity-type rapid sediment analyzer. The positions of cores and seismic reflection profile lines were also plotted at a scale of 1:80,000.

3. Scope.

This study concentrates on the geologic character of the subbottom and sediment distribution over most of Long Island Sound which covers nearly 3,400 square kilometers of the region between Connecticut and Long Island, New York (Fig. 1). The study area extends from Fishers Island (72°00' W.) on the east to near the East River (73°45' W.) on the west, close to New York City. Because of the nature of this study, area emphasis is on the nearshore parts of the Sound along the shores of Connecticut and northern Long Island in water depths from 3 to 30 meters; the central parts of the Sound at the eastern and western ends are also covered in some detail.

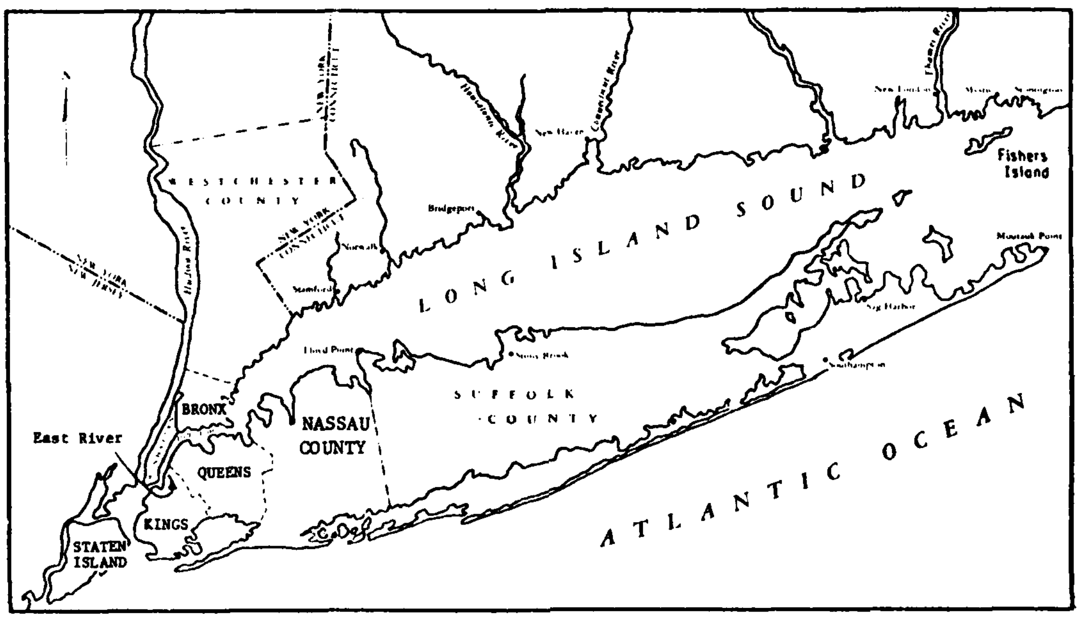

Figure 1. Regional map of Long Island Sound showing its relation to the Piedmont province of Connecticut and Atlantic Coastal Plain province of Long Island.

The field data used in this study consist of continuous seismic reflection profiles and vibratory cores shown in Figure 2. The data were collected in 1967 under contract with Alpine Geophysical Associates, Inc., and consist of 700 kilometers of sparker trackline acoustic profiles and 75 cores, 9 centimeters in diameter and a maximum of 5 meters long. The lengths of actual sediment recovered in the cores range from 1.3 to 5 meters. These primary data were supplemented by numerous reports in the technical literature and by use of the NOS 1:80,000-scale charts.

4. Geographic and Geologic Setting.

Long Island Sound, one of the largest estuaries on the east coast of the United States, has a general east-west orientation and is about 180 kilometers long with a maximum width of 45 kilometers in the center and narrows at both ends to about 18 kilometers wide. One of several basins that occupy the New England part of the Atlantic Coastal Plain province, it lies at the contact boundary between the crystalline Piedmont rocks and the Cretaceous Coastal Plain strata. Like the other basins to the east (Block Island Sound, Rhode Island Sound, Nantucket Sound, and Buzzards Bay), Long Island Sound is bounded on the south by till deposits from the southernmost terminus of the continental glaciers which occupied the region in the Pleistocene epoch.

The Connecticut coast of Long Island Sound is highly irregular with numerous embayments, islands close to shore, and coarse-grained sandspits and beaches. The coast is very rocky, dominated by Paleozoic-age crystalline bedrock and glacial debris, except for Triassic-age sedimentary rocks in the New Haven area. The four major rivers which drain Connecticut and flow into the Sound are the Thames, the Connecticut, the Quinnipiac, and the Housatonic.

The coast along the western half of northern Long Island is also highly irregular and is characterized by 10 recessed narrow bays which extend south and terminate at the Harbor Hill Moraine (Fig. 1); the eastern half has steep and high bluffs composed of unconsolidated glacial sediment which comprise the Harbor Hill Moraine that extends the entire length of Long Island. The moraine is continuous from the eastern end of Long Island at Orient Point to about Port Jefferson where it forms coastal bluffs with relief in excess of 100 meters that are directly exposed to wave erosion. West of Port Jefferson the Harbor Hill Moraine joins with the Ronkonkoma Moraine and both extend westward as a broken line of hills toward Staten Island and northern New Jersey.

5. General Stratigraphy of Long Island and Connecticut.

Detailed descriptions of the geologic units comprising Long Island are provided in Williams (1976); the units are summarized below and in Table 1. Figure 3 shows that Paleozoic-age crystalline bedrock underlies Long Island at depths to several hundred meters and rises toward Connecticut. Upper Cretaceous-age semiconsolidated sedimentary strata that overlie the bedrock surface are thin to the north but thicken southward under the Sound and underlie the Long Island mainland. The Lloyd, Raritan, and Magothy units consist of both marine and nonmarine sands and sandy clays and are important as freshwater aquifers on Long Island. Tertiary-age rocks are known to be present under the Continental Shelf south of Long Island but are absent on the island, probably as a result of uplift and extensive erosion in Tertiary time.

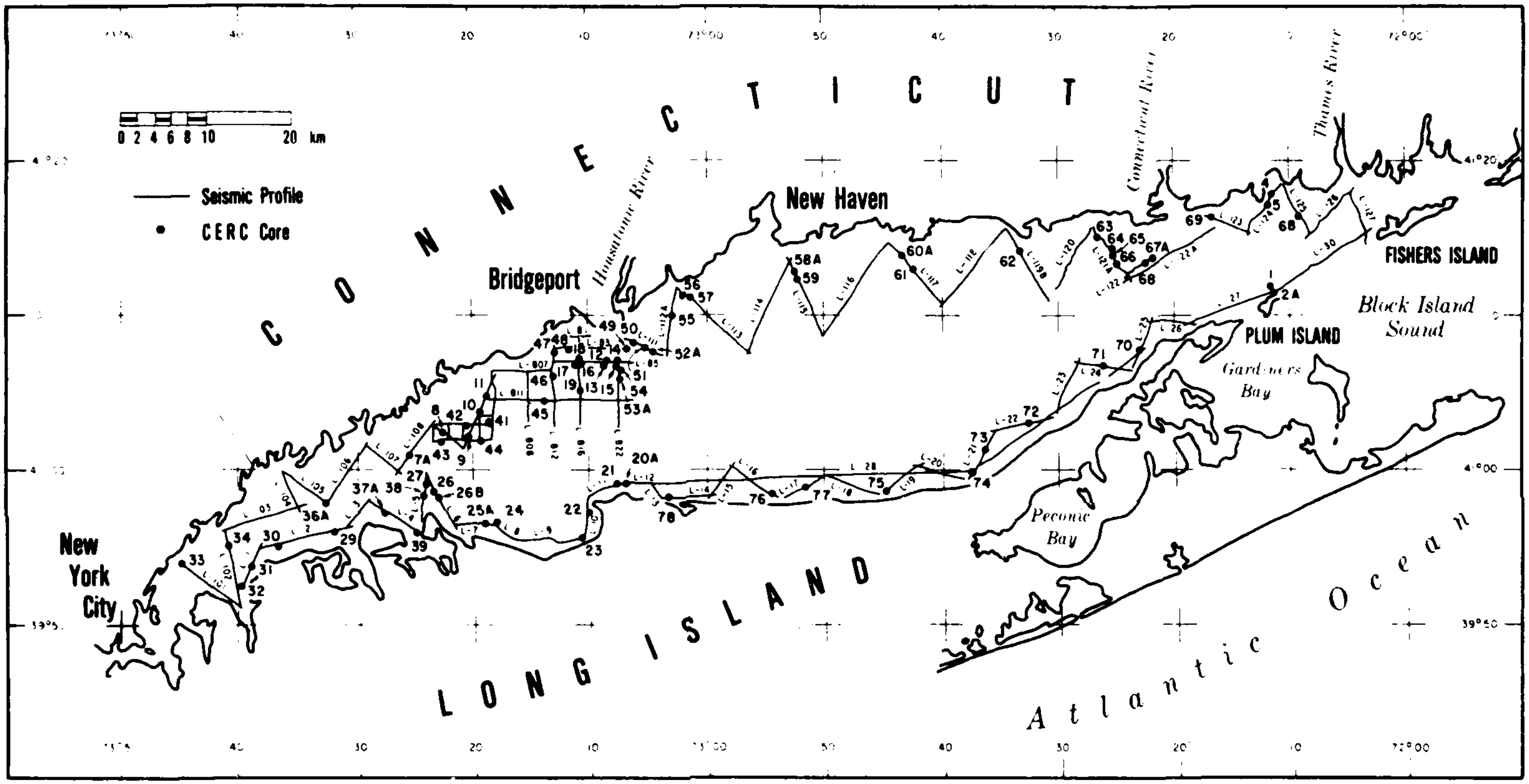

Figure 2. Trackline locations for the high resolution seismic reflection profiles and vibratory cores used in the study.

Table 1. Generalized stratigraphy of Long Island (from Williams, 1976).

Era	Period	Epoch	Unit	Character and origin of deposits
Cenozoic	Quaternary	Holocene (recent)		Quartzose sand, beach and dune deposits, and fine-grained lagoon sediments
		Pleistocene	Harbor Hill Moraine Ronkonkoma Moraine	Ground and terminal moraine; stratified deposits of sand and gravel, cobbles, and silt and clay
			20-foot clay	Grayish-green, silty clayey, glauconitic fine sand (marine)
			Gardiners Clay	Grayish-green, silty clay (marine)
			Jameco Gravel Mannetto Gravel	Fine to very coarse-sand and gravel; scattered beds of silt and clay (fluvial or glacial outwash)
Mesozoic	Cretaceous	Upper Cretaceous	Monmouth Group Matawan Group Magothy Formation	Quartzose sand interbedded with silt and clay
			Raritan Formation Raritan Clay	Silty, sand, brownish-gray clay with thin beds of sand and gravel
			Lloyd Sand	Quartzose fine to coarse sand and gravel; interbedded clay and silty sand is common
Precambrian or Paleozoic			Crystalline Bedrock	Undifferentiated, consolidated, metamorphic granite

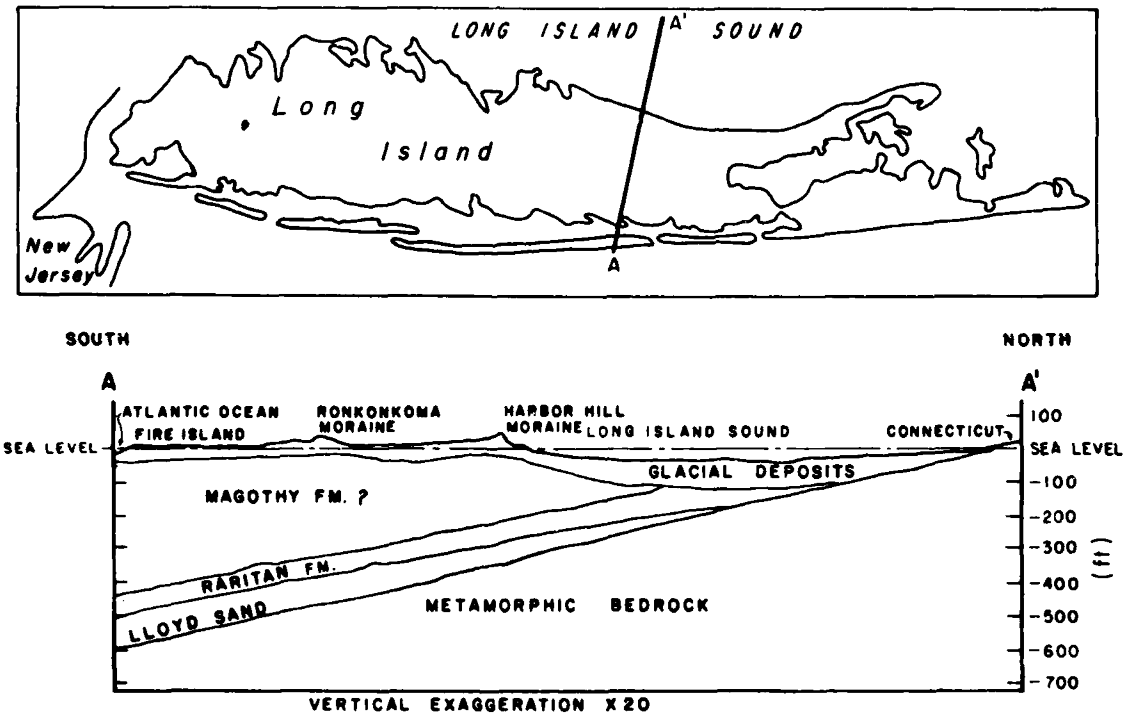

Figure 3. Geologic cross section from the south shore of Long Island at Fire Island north across Long Island Sound to the Connecticut mainland (modified from De Laguna, 1963).

Pleistocene-age till and outwash deposits from at least two glacial episodes overlie the Cretaceous strata and are responsible for much of the present-day relief on Long Island. Early Pleistocene glacial advances are thought to be represented by the Mannetto and Jameco gravels which are buried in places by the Gardiners clay which is believed to result from estuarine sedimentation during Sangamon time. Wisconsin Glaciation is well represented by the Ronkonkoma and Harbor Hill (terminal) Moraines and associated outwash sand plains that extend south of the moraines across the Long Island Inner Continental Shelf. The two moraines extend the length of Long Island and form the two forks at the eastern end.

The same bedrock surface that underlies Long Island forms nearly the entire mainland of Connecticut (Table 2). The only exception is in the New Haven area where a thick Triassic basin about 11 kilometers wide is present. To the east the basin is in fault contact with granitic bedrock; to the west the sandstones overlap the bedrock. Sanders (1963) first suggested that the basin continues south under the Sound and western Long Island, and this idea has been supported by results of magnetic surveys by Grim, Drake, and Heirtzler (1970). The bedrock surface of Connecticut has been deeply scoured by numerous glacial episodes and many of the river valleys were greatly deepened and widened; the bedrock is veneered with glacial deposits generally less than 10 meters thick except for the buried river valleys where thicknesses vary from 35 meters at the Housatonic River mouth to 244 meters at the Quinnipiac River (Upson and Spencer, 1964; Haeni and Sanders, 1974).

Table 2. General stratigraphy of Connecticut.

Era	Period	Epoch	Character and origin
Cenozoic	Quaternary	Holocene	Estuarine and marine soft organic muds from fluvial and shelf sources; modern marsh peat along coast
		Pleistocene	Localized and discontinuous ground till, moraine segments, and stratified sand and gravel outwash deposits
Mesozoic	Triassic		A basin of sandstone, siltstone, conglomerates and basaltic dikes intersect the shore at New Haven, Conn.; may continue under Long Island Sound toward the Long Island mainland
Paleozoic and Precambrian			Metamorphic and igneous crystalline basement rock

Along the north shore of Long Island, Holocene and modern sediments consist primarily of sands eroded from glacial bluffs exposed to wave attack. Fine-grained organic silts and clays in association with tidal marsh peat deposits are common from sea level to mean high water (MHW) along both the Long Island and especially the Connecticut shores, and thick accumulations of gaseous soft muds are present in the deeper parts of the Sound.

6. Bathymetry.

Detailed morphology of Long Island Sound is provided by NOS hydrographic charts and bathymetric maps at scales of 1:80,000 and 1:125,000, respectively.

The major bathymetric trends and features from the NOS maps with seven selected profile locations are shown in Figure 4; the cross-sectional profiles across the Sound are illustrated in Figure 5. Based on bathymetry, the Sound is divided into five major basins separated by shoals that have considerable relief.

The western basin (profile A in Fig. 5) is rather narrow and water depths to 27 meters are common in the center but greater depths are present in small depressions. The central part of the Sound is composed of three basins with Cable and Anchor Reef, Stratford Shoal, and Six Mile Reef acting as the bounding shoals. Depths in the central basins usually do not exceed 30 meters, but some holes on the Long Island side extend to -46 meters. The eastern basin (profiles F and G in Fig. 5) has considerably more relief, and depths in the elongate troughs may exceed 91 meters, such as "The Race" in profile G.

7. Previous Geologic Investigations.

Long Island Sound is probably one of the most studied areas in the United States. Dana (1890) was one of the first to speculate that based on land surface morphology and depth contours the ancient "Sound River" flowed eastward toward Block Island Sound and was responsible for eroding the trough that became Long Island Sound when sea level rose to its present position. However, Veatch (1906) judged that the Sound River flowed west rather than east and breached western Long Island to join the sea. Fuller's (1914) study of the glacial deposits on Long Island gave support to Dana's eastward-flow theory for the Sound River but he believed that the major erosion took place in late Tertiary or early Pleistocene time, and that much of the present morphology of the Sound was the result of glacial erosion and depositional processes during late Wisconsin time. Fleming's (1935) study of central Long Island and its glacial geology pointed out that the Ronkonkana and Harbor Hill Moraines are composed mostly of stratified ice contact or glaciofluvial sand and gravel rather than till deposited directly at the glacier terminus.

Investigation of the Sound continued with studies of the surface deposits on Long Island and Connecticut; however, in the 1950's new geophysical equipment was developed that allowed researchers to survey the Sound and look at the subbottom to give a third dimension to its geologic character. Oliver and Drake (1951) were about the first to use seismic refraction data to show that a very uneven bedrock surface underlies the Sound and is covered with glacial-age unconsolidated sediments. They were unable to identify Cretaceous strata in the Sound that were known to form the core of the Long Island mainland.

Ellis (1962), in a detailed study of the sediments and geologic history of the Norwalk Islands between Stamford and Bridgeport, Connecticut, stated that the island chain was underlain by bedrock but that glacial till from a terminal moraine younger than the Harbor Hill formed most of the islands' relief.

Upson and Spencer (1964) used deep boring logs from bridge foundation projects to describe the subbottom configuration and fill sediments of the ancestral channels of the Housatonic, Quinnipiac, and Thames Rivers that discharge into Long Island Sound. They found that all the valleys were eroded by glacial processes to bedrock and subsequently nearly filled with a sequence of glacial till, outwash sand and gravel, and estuarine silt and clay. Sanders (1965) and Haeni and Sanders (1974) used well boring logs and continuous

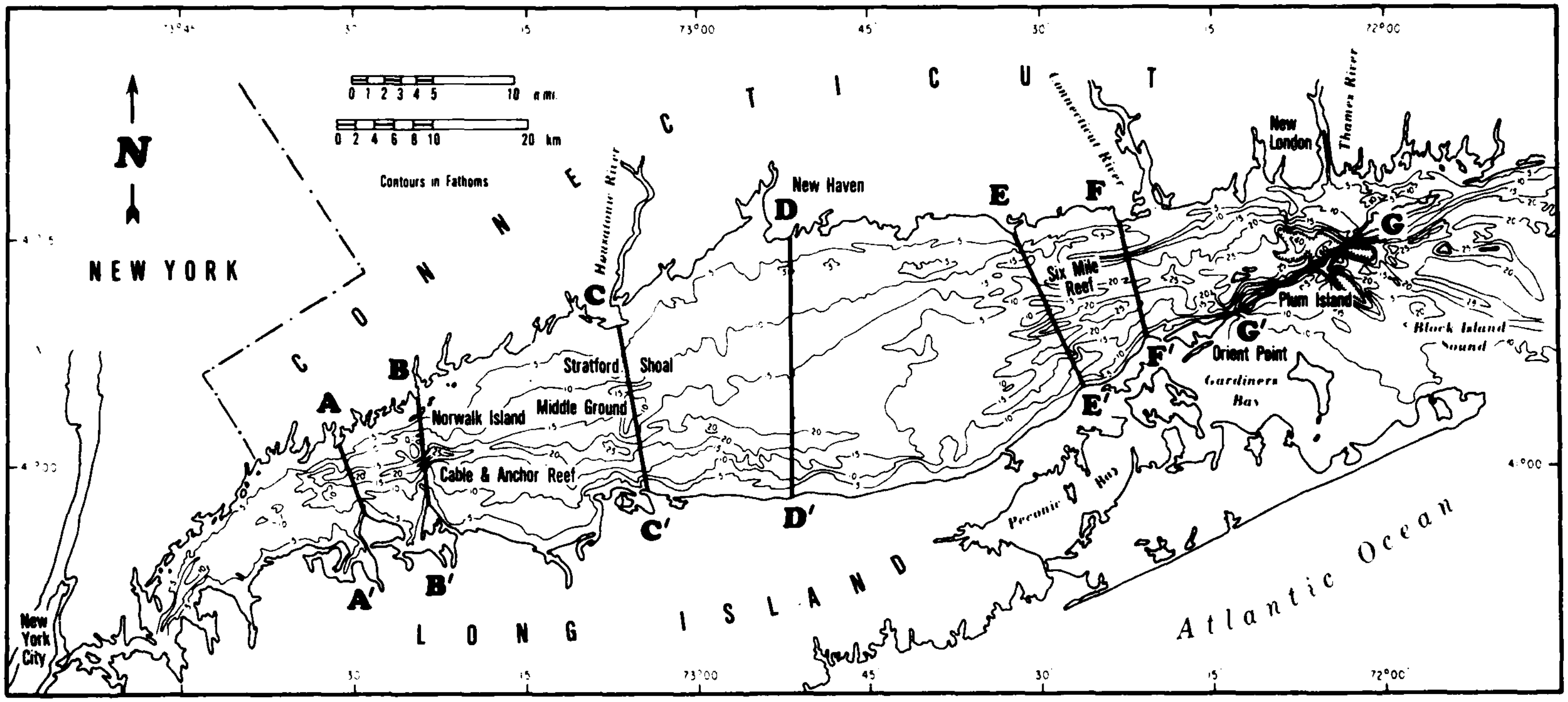

Figure 4. Bathymetry of Long Island Sound showing the major land and shoal features. The seven cross-sectional profiles are illustrated in Figure 5.

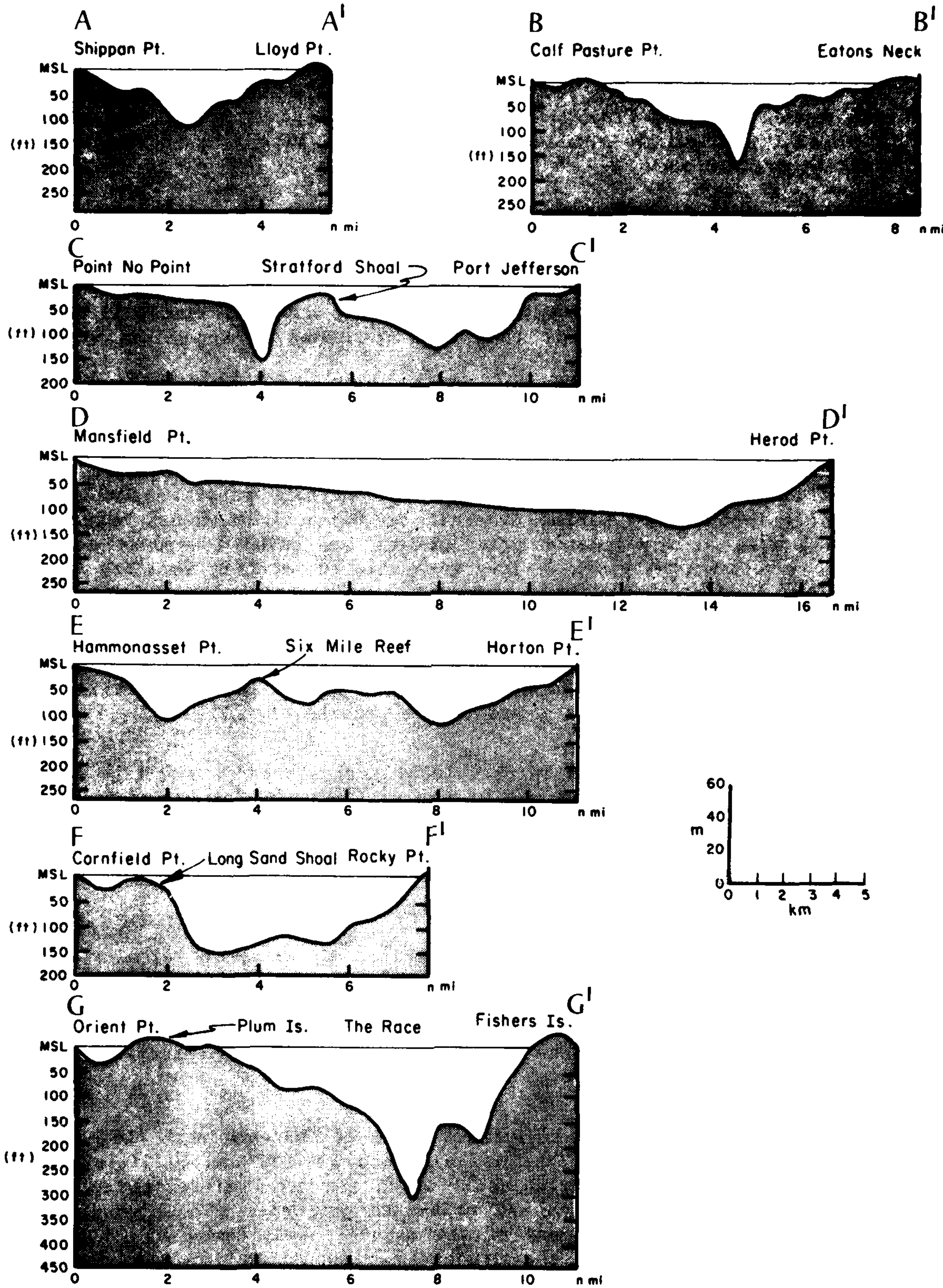

Figure 5. Cross-sectional profiles of the Long Island Sound sea floor. See Figure 4 for profile locations.

seismic profiles to map the bedrock configuration of the ancestrial Quinnipiac River valley that underlies New Haven Harbor to depths of -224 meters and is about 2 kilometers wide. It is the deepest of any of the river valleys entering the Sound and apparently follows Triassic faults and projects southwest into the Sound. Sanders (1965) described one boring that showed the upper 35 meters of fill sediment is sand and gravel outwash with frequent occurrences of estuarine organic mud.

Presence of varved lacustrine deposits in coastal areas adjacent to the Sound led several investigators (Antevs, 1928; Frankel and Thomas, 1966; Bertoni, Dowling, and Frankel, 1977) to surmise that one or more large freshwater lakes occupied the Sound during the Pleistocene epoch. Upson and Spencer (1964) and Williams (1976) show that these deposits also fill many of the deeply eroded river channels that were connected to the Sound when sea level was below present levels.

Akpati (1970; 1974) reported results of a study on the surfacial sediments and foraminiferal ecology of eastern Long Island Sound to Fishers Island Sound. He examined grain textural properties and mineral compositions at 53 sites, including 3 of the CERC cores included in this report. Donohue and Tucker (1970) reported on marine minerals in Connecticut waters based on a program of coring at 8-kilometer grid spacing and using low-power acoustic profiling and bottom photography. They were able to identify some deposits of sand and gravel and certain heavy mineral concentrations, but the results appear to be of limited value for resource evaluation. The Pleistocene and Holocene history of the western Long Island region was studied in detail by Newman (1966); he reported evidence that a large glacial lake occupied the Sound region before the last ice advance, and that the sea began filling the Sound subsequent to about 12,000 years before present (B.P.).

In 1970, the New York Ocean Science Laboratory started a study in eastern Long Island Sound to determine residual drift patterns of the surface and bottom waters. A preliminary report by Hollman and Sandberg (1972) showed that the Sound was stratified with surface waterflow out of the Sound at an average speed of 6 centimeters per second, and bottom waterflow into the Sound at 1.2 centimeters per second.

Grim, Drake, and Heirtzler (1970) summarized 10 years of seismic reflection and magnetic survey work on the subbottom character of the Sound. They report that the Paleozoic bedrock and Cretaceous sedimentary rocks are highly dissected and irregular with relief on the order of scores of meters and that Pleistocene and Holocene sediments fill most of the relief surfaces to produce the present rather shallow and even bottom.

In eastern parts of Long Island Sound where it connects with Block Island Sound, McMaster and Ashraf (1973a, 1973b), Coch (1974), and Williams (1976) identified deeply buried stream channels which are pre-Pleistocene but acted as conduits for glacial advances and melt-water streams. These studies are germane to this study because many of the channels originated in Connecticut and traversed the Sound, and the processes responsible for the subbottom geologic character are similar throughout the entire southern New England region.

Feldhausen and Ali (1975) performed multivariate analysis on grain-size data from 57 sample sites in the central and western basins of the Sound and identified 5 distinguishable sedimentary facies. They then related the facies to environments of deposition and subsequent modification by wind- and tide-generated currents. A major conclusion was that the rivers entering the Sound at present contribute minor volumes of sediment.

Bohlen (1975) reported results of a 2-year study to measure the suspended-sediment budget at 11 sites in eastern Long Island Sound. In contrast to other studies which show the central and western basins to behave like an estuary, Bohlen found that the eastern basin is well mixed and dominated by wind stress, tidal currents, and river discharge.

For about the past 5 years, a group of researchers at Yale University has been reporting on studies done primarily in the central and eastern basins. Gordon (1974) examined by quantitative means the settling processes and dispersion of dredge material dumped at the authorized dump ground off New Haven. Gordon and Pilbeam (1975) established bottom current meters at 28 stations to measure current velocities and the relationship to transport of bottom sediment. Bokuniewicz, Gebert, and Gordon (1976) used high-resolution acoustic profiles and short cores to estimate the areas and volumes of the unconsolidated sediments in the entire Sound in an attempt to produce a total sediment budget. One conclusion was that the volume of estuarine muds in place greatly exceed volumes that could have been supplied by rivers over the past 8,000 years and they propose that the open shelf is a primary source. Bokuniewicz, Gordon, and Kastens (1977) presented results of a study on the morphology and migration of a field of large sand waves (up to 4 meters high) in eastern Long Island Sound. They reported that sand waves will not form if more than 10 percent mud or 12 percent coarse sand (or larger) is present, and that most waves were asymmetric to suggest transport into the Sound predominates.

Recent studies by Sirkin (1976), Flint and Gebert (1976), and Newman (1977) have shown that late Wisconsin Glaciation in the Long Island region has been very complex and that the moraines and outwash deposits are often superimposed. Also, there is clear evidence that glacial advances younger than the one that left the Harbor Hill Moraine on the north of Long Island have occurred, and their discontinuous moraines are still present.

II. GEOMORPHOLOGY AND SHALLOW SUBBOTTOM CHARACTER

1. Shallow Subbottom Structure and Stratigraphy.

Examination of the 700 kilometers of acoustic profiles collected shows that four major horizons or reflection units are present in Long Island Sound within the depth and resolution range of the equipment, usually about 91 and 0.5 meter, respectively. These are: (a) the floor of the Sound or sediment-water interface; (b) the top of Pleistocene sediments which include subreflectors from glacial till, sand and gravel outwash, and lacustrine fine-grained strata; (c) the glaciated surface of Cretaceous-age semiconsolidated sedimentary rocks; and (d) the deeply dissected and smoothed surface of pre-Cretaceous consolidated rocks consisting of Precambrian and Paleozic bedrock and possibly Triassic strata in the region between New Haven and Northport, Long Island. The findings in this report agree with much of the basic information contained in Grim, Drake, and Heirtzler (1970) concerning the subbottom geologic character of the Sound, though use of the sparker profiles in conjunction with the cores has provided more detail in many areas.

a. Sea-Floor Reflector. The reflective character of the sea floor is dependent on the type of sediment comprising the upper parts of the sediment column. The Sound is generally floored by sands and gravelly sand along the north shore of the Long Island mainland and adjacent to many of the islands, shoals, and reefs in the middle of the Sound, as well as toward the Connecticut shore where glacial till and outwash detritus were deposited and subsequently reworked by waves and currents. Modern muds composed of silt, clay, and organic matter cover much of the central Sound and along the Connecticut shore. The following three types of areas shown on the seismic profiles are identified with the core information:

(1) Type 1. The first type denotes a very soft bottom where the upper several meters are composed of sandy silt or mud with high contents of organic matter and gas. Records in these areas are almost opaque with a marked absence of any subbottom reflectors. The soft bottom acts as a sponge to the acoustic signal, absorbs the energy and prevents any significant penetration to the deeper reflectors.

(2) Type 2. The second type shows a high degree of stratification starting at the surface and continuing with depth and allows the best penetration to reveal the subbottom character. The cores show that these areas are usually medium- and coarse-grained sands deposited as deltas and outwash fans. Often the surface in these areas has sand waves and megaripples as the result of the sediment being actively transported primarily by tidal currents.

(3) Type 3. The third reflector type is normally very dark or strong on the seismic records and the region beneath is very light, showing only faint subbottom reflectors. Because the bottom is so hard there are normally three or more multiple reflectors on the profiles. These areas are characteristic of regions where consolidated bedrock is very close to the surface, where compacted glacial till is present and there are parabolic reflectors in the water column suggesting presence of boulders on the surface, and where very compact and well-sorted fine sand makes up the sea floor.

b. Pleistocene Sediments. The reflectors and sedimentary deposits assigned to a Pleistocene age are by far the most abundant and the most complex of any in the study area. Most of the information identifying the various subreflectors is based on published geologic studies of the New York and Connecticut mainland and of Long Island where only Pleistocene deposits overlie the Paleozoic and Cretaceous bedrock. Although most of the Pleistocene deposits are depositional, there is evidence of erosional episodes where channels have been downcut or widened and deepened by glacial or fluvial erosion and areas have been subjected to subaerial erosion.

The thickest Pleistocene sediments occur in the bedrock valleys and channels where highly stratified and thinly bedded strata conform to the topography of the underlying bedrock (Fig. 6). Where these sediments have been penetrated by deep borings or exposed in surface excavations, they are thinly

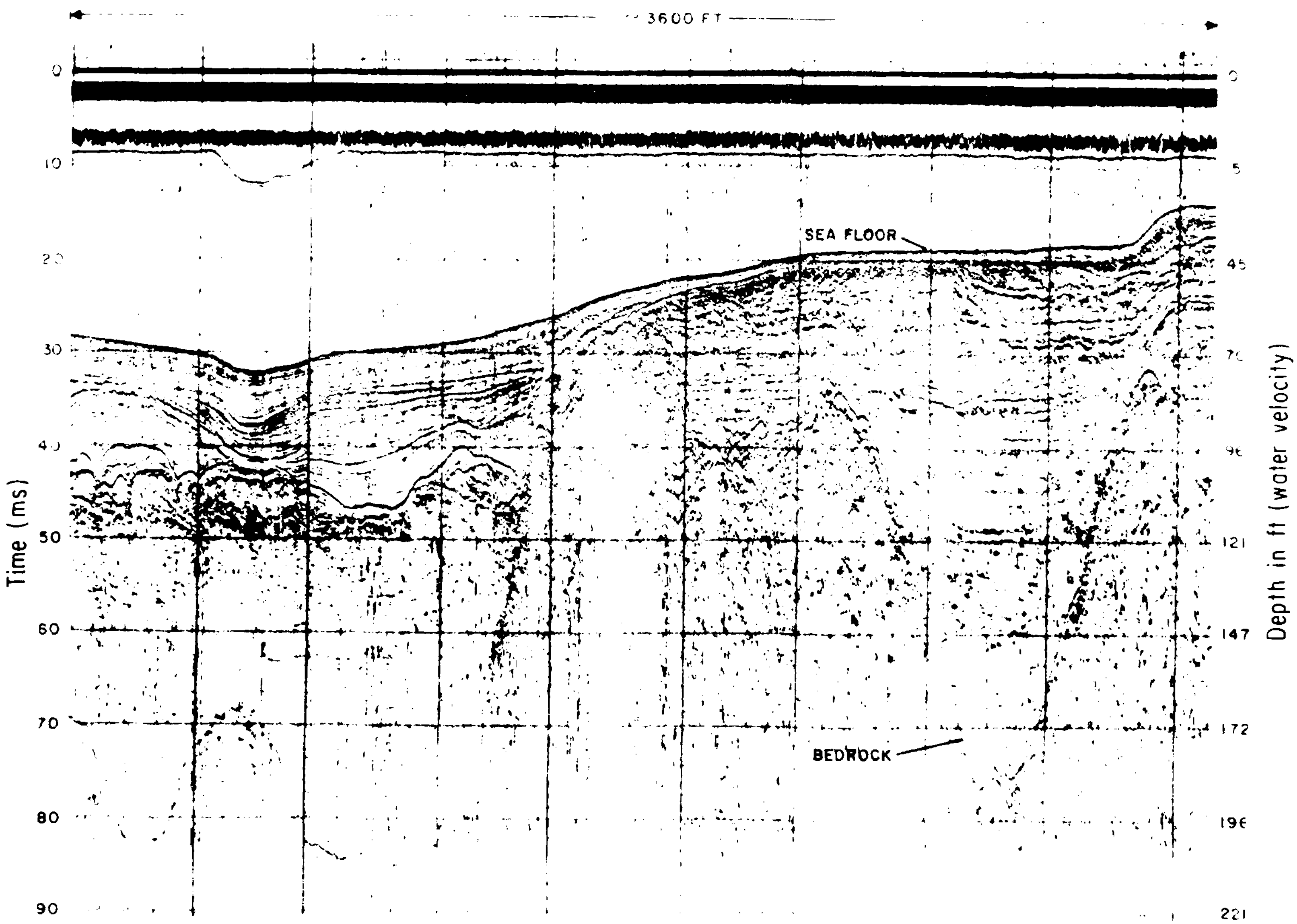

Figure 6. Typical seismic profile off the Norwalk Islands, Connecticut, showing the irregular and high-relief bedrock surface filled and covered by highly stratified fine-grained sediments and glacial sands.

laminated silt and clay with partings of fine sand. Their appearance closely resembles varve sequences related to seasonal sedimentation under quiet, low-energy conditions (Fig. 7). The surface elevation of this unit, termed the Flushing Formation by Newman (1977), varies considerably from near sea level to about -40 meters; its thickness has been documented by Williams (1976) to be 137 meters in the Orient Point buried channel and could be as much as 240 meters in a deep valley that runs southwest into the Sound at New Haven Harbor. The origin of the deposits is long-term lacustrine deposition related to glacial Lake Flushing that occupied deeper parts of the Sound from 15,000 to about 13,500 years ago (Newman, 1977). This lake was created immediately after retreat of the Harbor Hill glacier from Long Island and probably was formed by damming of channels in the Block Island Sound region by glacial fill. The exact lateral extent of these lake deposits is difficult to determine but similar, and probably related deposits, are present in deep valleys on the western end of Long Island and in the valley just south of New Haven; similar strata have been reported in eastern Long Island Sound and even parts of Block Island Sound (Bertoni, Dowling, and Frankel, 1977). The acoustic profiles from this survey also show that most of the central parts of the Sound contain stratified sediments overlying bedrock.

The remainder of the Pleistocene sediments directly overlie either the lacustrine beds or bedrock and consist of glacial till and stratified deltas and outwash fans (mostly composed of sand and gravel) that originated adjacent to the moraines or as deposits from the melt-water streams that drained from the glaciers. As an economic resource these deposits are by far the most important, and their extent and character are covered in detail in the next section.

The late Wisconsin-age Harbor Hill Moraine is nearly continuous across the entire north shore of Long Island and has been studied by many researchers interested in Pleistocene glacial events. It apparently resulted from a glacier that covered the Sound and parts of New England to the north, but much of the moraine actually consists of kame and kettle deposits marked by a high degree of stratification. The seismic profiles off the north shore of Long Island show no evidence of actual till deposits present. The shoreface region to depths of -18 meters consists of lobate and coalescing fans and deltas made up of medium- and coarse-grained sands that are outwash from the Harbor Hill Moraine.

A number of researchers have recognized evidence, in the form of short, discontinuous, low-relief moraines, that glaciers younger than the Harbor Hill advance have occupied the Connecticut mainland. Goldsmith (1960) identified the Ledyard Moraine about 13 kilometers north of the Sound near New London, and also showed the position of the Middletown Moraine about 32 kilometers north of the Sound in central Connecticut. He attributes these moraines to temporary halts in the retreat of the glacier that formed the Harbor Hill Moraine. More recently, Flint (1968) and Flint and Gebert (1976) described the form and composition of the Madison and Old Saybrook Moraines on the coast east of New Haven (and their seaward extensions) and the Lordship outwash head southeast of Bridgeport.

Flint (1968) was never able to locate or identify the moraine that had formed the Lordship outwash head but he speculated that it was possibly a western extension of the Madison or Branford Moraines, and that the outwash

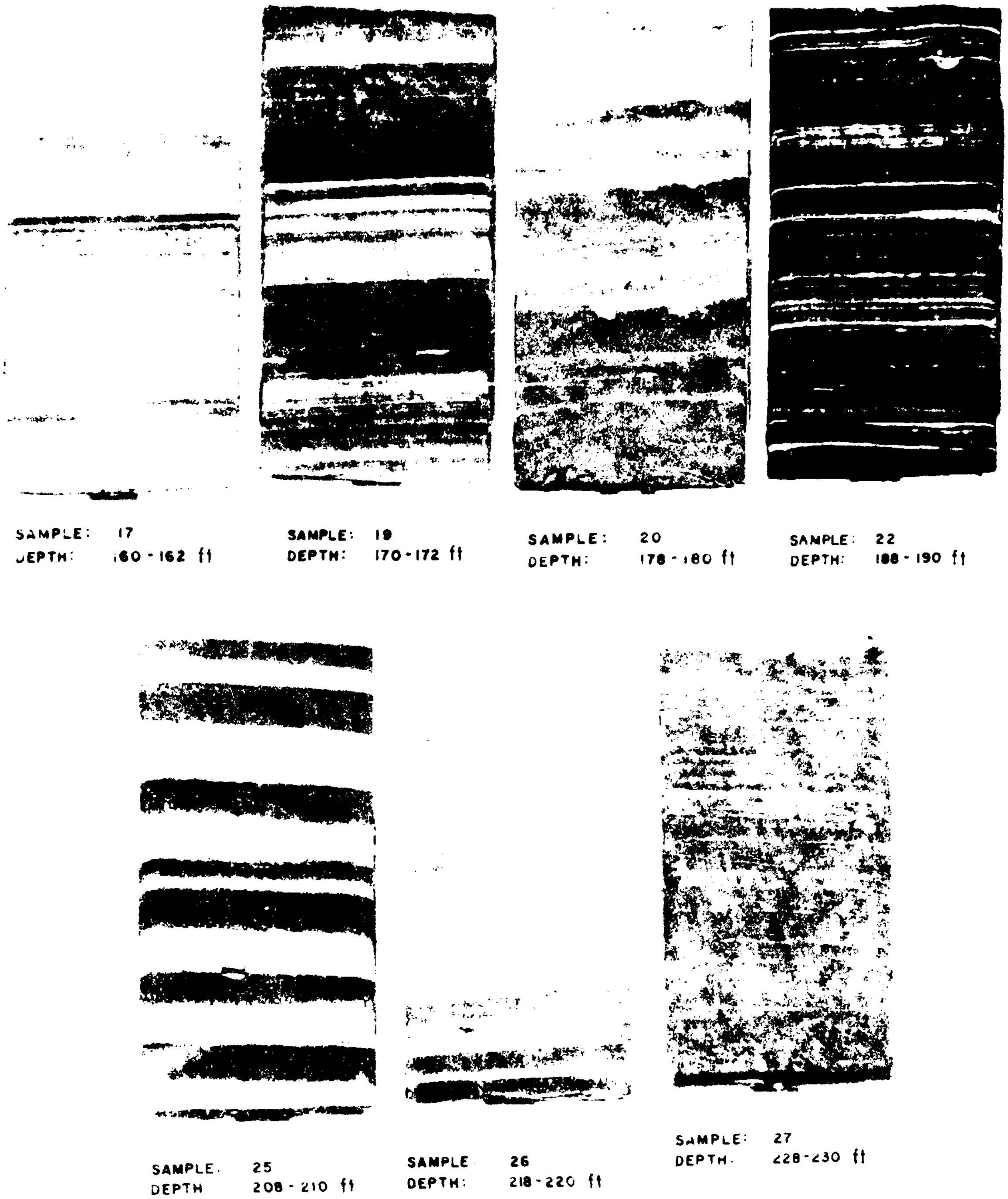

Figure 7. Photos of apparent varve sediments retrieved in the Orient Point boring drilled into the Orient Point buried channel. These suggest a major glacial lake occupied the Long Island and Block Island Sounds during Pleistocene time. Each pair of light dark lines represents a summer and winter episode of lacustrine deposition (from Woodward-Clyde-Sherard and Associates, 1965).

fan resulted from deltaic sedimentation by the Housatonic River as it flowed south through the moraine. The Lordship head has a maximum dimension of almost 16 kilometers and extends well into the Sound, and is one of the most promising areas for sand and gravel. Using acoustic profiling equipment, Flint and Gebert (1976) surveyed areas of the Sound online with the Madison and Old Saybrook Moraines and were able to differentiate between bedrock islands close to the Connecticut shore and seven shoals and islands composed of till which are the morainal extensions. Their conclusions are also supported by this study. Figure 8 shows that Crooked Shoal, Branford Reef, and Townshend Ledge are seaward extensions of the Madison Moraine, and that Kimberley Reef, Falkner Island, Goose Island, and an unnamed shoal represent extensions of the Old Saybrook Moraine.

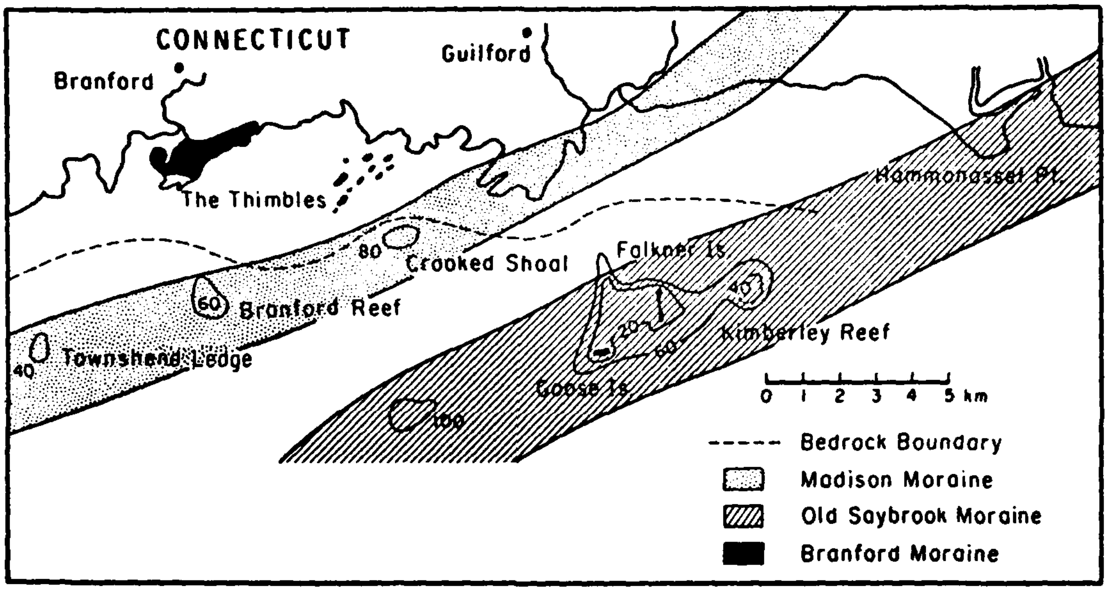

Figure 8. Map of coastal Connecticut from Branford to Hammonasset Point showing the location and alinement of several shoals and islands determined to be remnants of the Madison and Old Saybrook Moraines (modified from Flint and Gebert, 1976).

In western Long Island, Newman (1977) identified the Elmhurst Moraine immediately north of the Harbor Hill Moraine in Queens County, Long Island, as an irregular and curving line of kame deposits (Fig. 9). Based on its northeast strike, Newman extended the moraine into the Sound where it continues northeast defined by the shoal contours of Execution Rocks and the elongate shape and position of the Norwalk Islands.

Based on radiocarbon dating, Newman (1977) believes that the Elmhurst glacial advance occurred about 13,500 years B.P. and was part of the Port Huron readvance that took place in the Great Lakes region. The geologic events are summarized in Table 3.

The profiles and cores collected in this study have been useful in identifying additional glacial depositional features shown in Figure 10. About 7.2 kilometers south of the Old Saybrook Moraine, a moraine segment almost 9

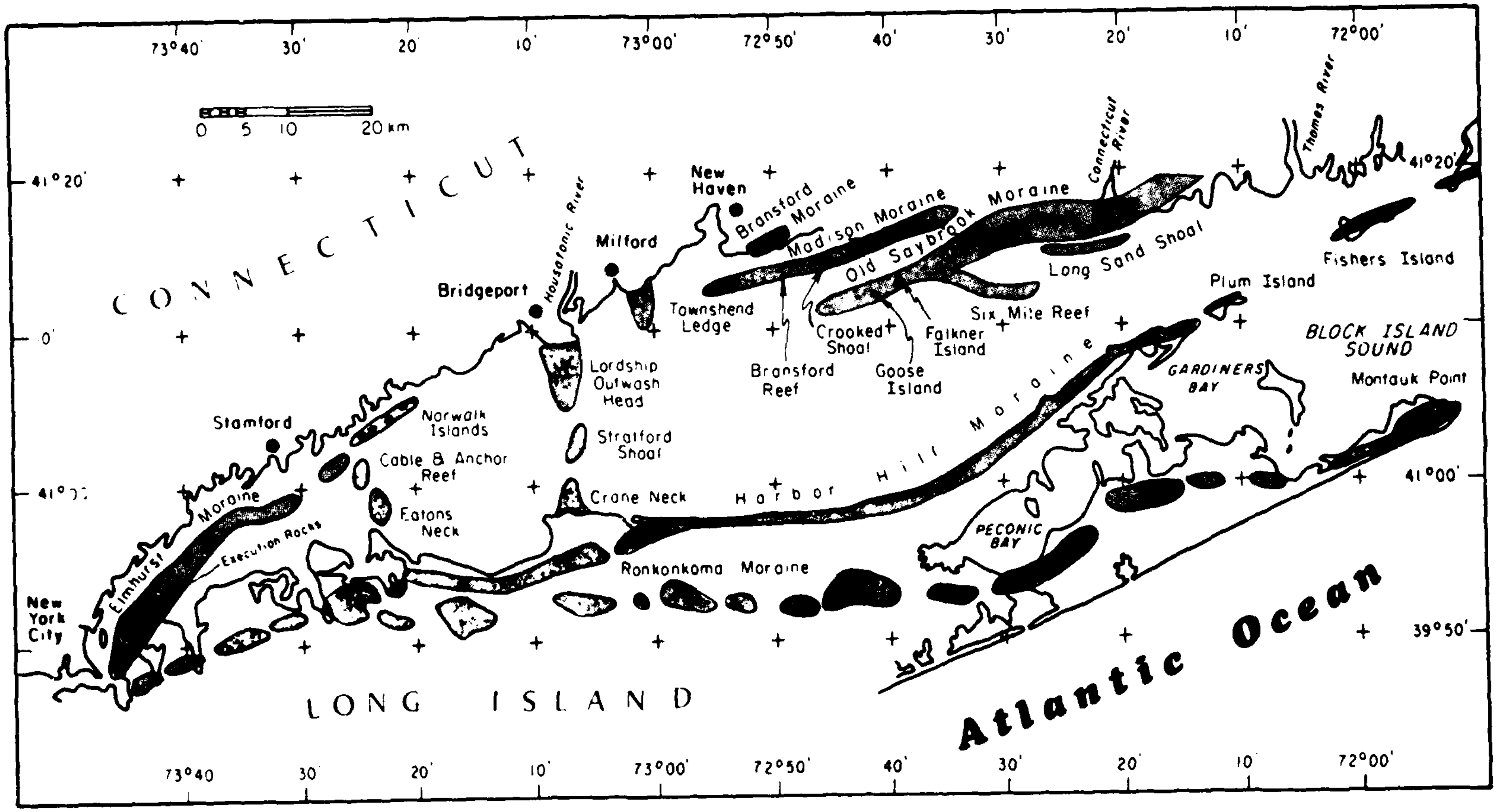

Figure 9. Late Wisconsin-age Harbor Hill and Ronkonkoma Moraines extend along Long Island, but there is good evidence for younger moraine segments and outwash features to the north in Long Island Sound and along the Connecticut coast (discussed in text).

Table 3. Summary of Quaternary geologic events (dates from Newman, 1977).

Age (yr)	Event
12,300 to present	As sea level rose, Long Island Sound became a tidal estuary and deposition of organic muds and sandy silts occurred. Sources of these sediments were and continue to be coastal erosion of glacial deposits, rivers draining glacial terrain, and sediment influx from Block Island Sound and the adjacent Continental Shelf.
13,400	Short-term readvance or slowing of retreat of the glaciers that were part of the Port Huron stade. This led to deposition of the several discontinuous terminal moraine segments (Elmhurst, Madison, Old Saybrook, Six Mile, Ledyard, and Middletown) close to the Connecticut coast on Long Island Sound.
15,000 to 13,400	Damming by the Ronkonkoma and Harbor Hill Moraines backed up freshwater and created Lake Flushing that covered much of Long Island and Block Island Sounds. Very fine grained silt and clay were deposited as seasonal varves filling in and covering the high-relief bedrock surface and glacial deposits.
21,000 to 15,000	Late Wisconsin advance of the glacier resulted in deposition of the Harbor Hill Moraine consisting of till and stratified kame and outwash deposits. Existing river valleys were deepened and widened.

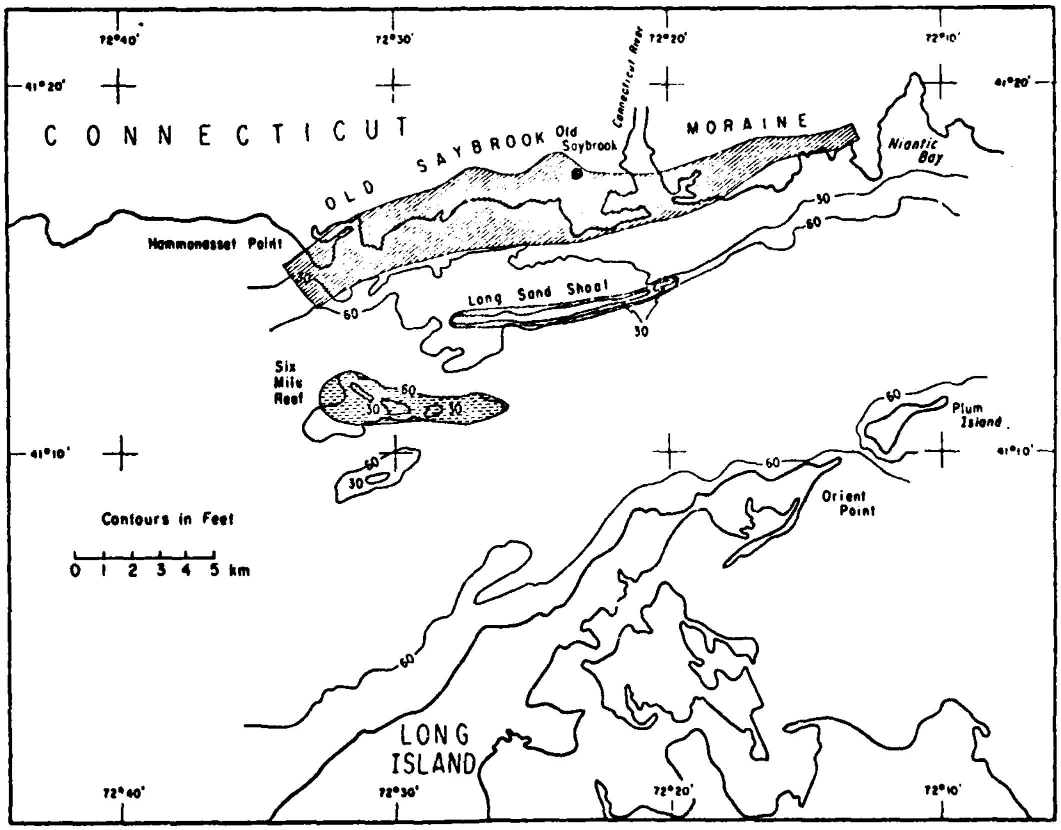

Figure 10. Flint and Gebert (1976) have shown that the Old Saybrook Moraine is present along the Connecticut coast from Niantic Bay to Hammonasset Point and then extends southwest into the Sound. Results of this study reveal that Six Mile Reef is a moraine segment and Long Sand shoal originated as an outwash deposit that has been lengthened to the west by estuarine processes.

kilometers long and 1.8 kilometers wide is clearly defined on the two trackline profiles by its irregular subbottom character and almost 22 meters of sea-floor relief. The segment, named Six Mile Reef on the charts, represents the most southerly advance of very late Wisconsin Glaciation following the Harbor Hill episode. Its proximity to the Old Saybrook Moraine probably represents a seaward extension of that moraine, but additional subbottom data are needed to verify this.

In the western Sound, segments of the Elmhurst Moraine were identified on several seismic records as subtle, broad mounds covered by about 5 meters of modern sediments (Fig. 9).

Position of the Elmhurst Moraine in Figure 9 is close to what Newman (1977) theorized; at Execution Rocks it is about 1.8 kilometers wide and strikes east-northeast parallel to the Connecticut shore in an irregular and lobate line. South of Stamford Harbor the moraine is marked by several prominent shoals and to the east it is perched on a bedrock high and comprises the Norwalk Islands. Its trend continues toward Bridgeport and is no doubt responsible for the Lordship outwash head southeast of Bridgeport (Fig. 9). Another submerged outwash head located south of the town of Milford very likely marks the terminus of the moraine west of New Haven Harbor. The Branford Moraine segment east of New Haven is probably a continuation of that outwash head, but the proximity of the Madison, Old Saybrook, and Six Mile Reef segments suggests the glacier front had several small-scale advances and retreats in eastern parts of the Sound.

In addition to the actual moraine features found, a number of highly stratified and elongate shoals containing very coarse-grained sediments are present in the Sound which apparently owe their origins to glaciofluvial or ice-contact processes. Acoustic profiles and core 7 at Cable and Anchor Reef (Fig. 11) show that about 10 meters of very coarse sand in the form of forset strata rests on a bedrock high which continues south toward Long Island and meets the shore at Eatons Neck. Its proximity to the moraine forming the Norwalk Islands suggests a relationship; however, its general north-south orientation is normal to any other glacial deposition feature. A similar condition exists for Stratford Shoal in the middle of the Sound south of Bridgeport (Fig. 11). The shoal is 5.4 kilometers long with a north-south axis, and the seismic profiles suggest that the presence of stratified till or outwash overtop a bedrock high. The exact origins of these anomolous north-south features are not definitely known, but their form, forset-type stratification, and coarse sand and gravel composition suggest that they are outwash deltas from the ancestral Housatonic and Naugatuck Rivers. Additional investigations are needed to better understand their origins.

Long Sand Shoal off the mouth of the Connecticut River is another sea-floor feature that originated from very late Wisconsin glacial processes. Its east-west orientation, asymmetric profile, and high relief suggest a morainal origin, but acoustic lines over the shoal show a high degree of internal stratification with forset strata dipping south; bedrock beneath the shoal is very high but there is no evidence of till reflectors. Cores obtained from the shoal show a composition of clean and generally moderately sorted sand, which suggests that it was a delta-front or outwash head that has probably been narrowed and significantly increased in length by Holocene estuarine processes during the past 12,000 years.

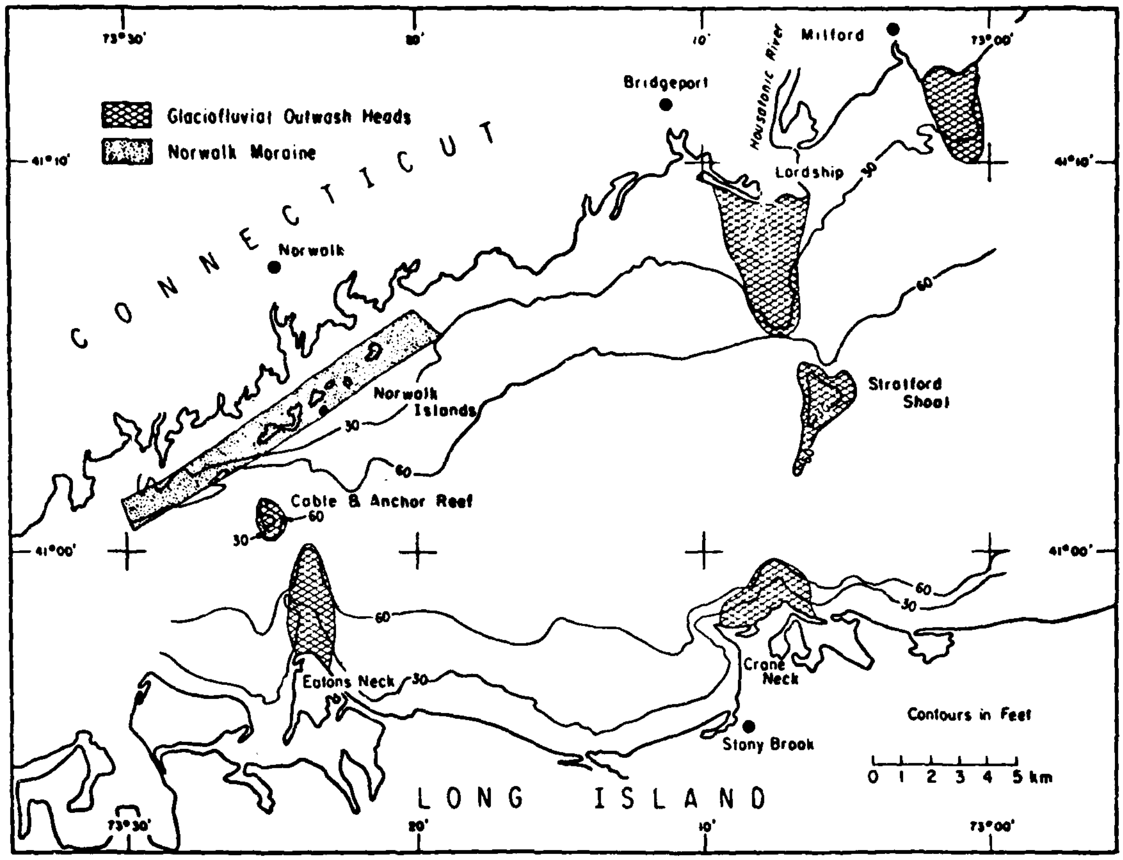

Figure 11. The Norwalk Islands of Connecticut are remnants of a late Wisconsin moraine extending discontinuously from Queens County, Long Island, northeast to the New Haven area. The Lordship and Milford outwash deltas associated with that moraine and the positive relief features at Cable and Anchor Reef, Eatons Neck, Stratford Shoal, and Crane Neck also appear to have a glacial origin.

c. Cretaceous and Paleozoic Bedrock. The acoustic reflector marking the top of the bedrock is the strongest and most continuous of any on the records (Fig. 12). Except in deep channel areas such as off New Haven, in central parts of the Sound, and along much of the north shore of Long Island, the bedrock is present on the records. However, it is difficult to differentiate Cretaceous strata from underlying Paleozoic rock because of limited resolution on some profiles and lack of penetration into the Cretaceous strata. The exact northern limits of the Cretaceous cuesta are difficult to determine, but they appear to be close to the north shore of Long Island in the east and strike west through the center of the Sound in the vicinity of Stratford Shoal and then underlie the northern neck areas of western Long Island.

The surface character of the bedrock is of extremely high relief, and contour patterns are difficult and at times impossible to identify in certain areas because of the extent of massive downcutting and widening of then existing channels by the glaciers and melt water. In the western Sound, several large channels are present on both the Connecticut and Long Island sides and all appear to deepen toward the center of the Sound. Williams (1976) described six channels with thalwegs reaching -61 to -145 meters that underlie the recessed bays of northwestern Long Island and apparently transect the

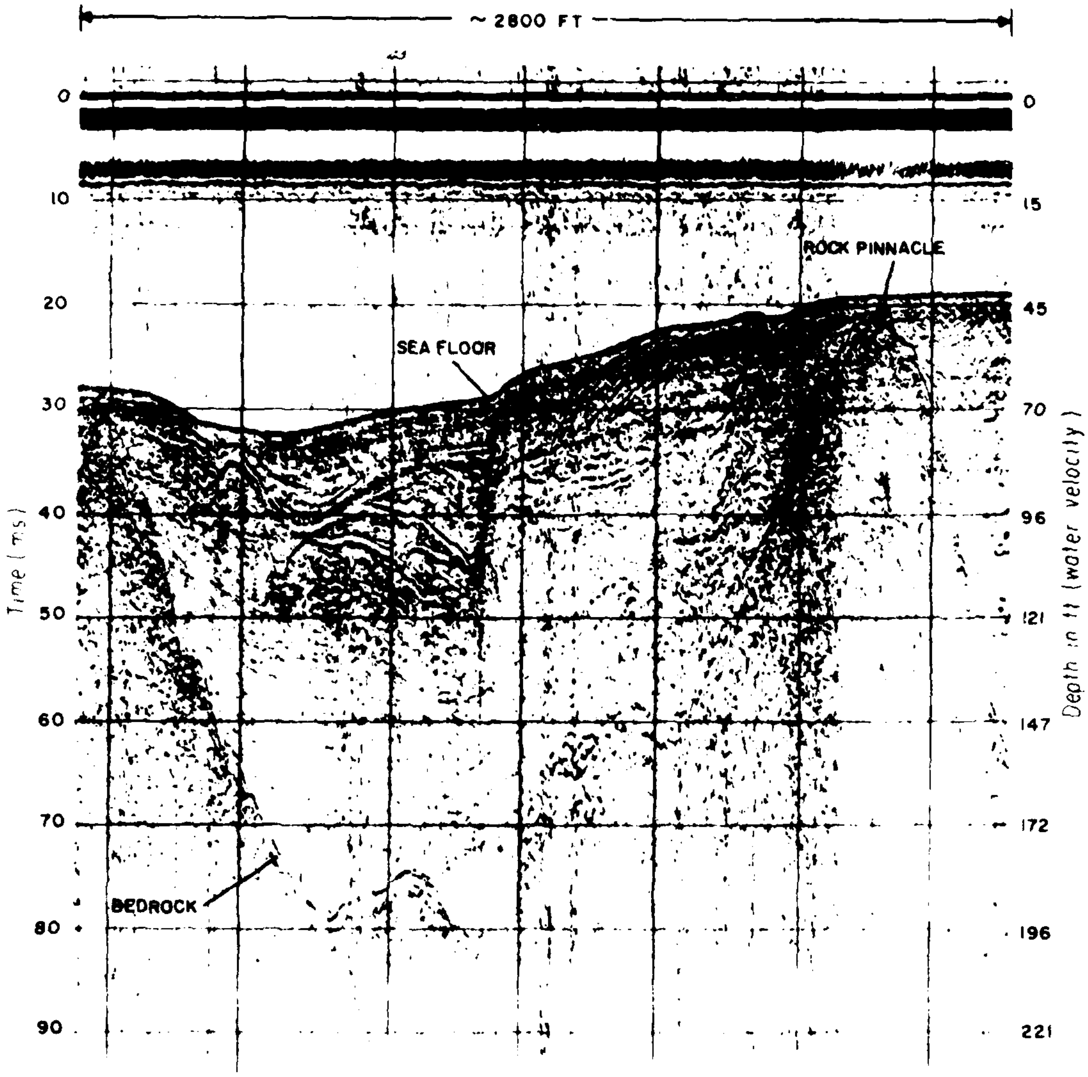

Figure 12. Typical seismic profile of a glaciated bedrock channel filled with Pleistocene sediments. Bedrock to the right nearly crops out at the sea floor.

island and continue south across the shelf to intersect the present Hudson shelf channel. However, the connections with channels in the Sound have apparently been obliterated by glacial erosion because contour patterns do not match. Also, the unusual channel depths and reverse gradients to the north are the result of massive glacial erosion as the terminus remained at the Harbor Hill Moraine.

In central parts of the Sound the bedrock surface is generally well below the depth range of the sparker records; however, Grim, Drake, and Heirtzler (1970) show a well-developed, characteristic glaciated east-west valley paralleling the north shore of Long Island from Port Jefferson east to about 72°30' W. The sparker profiles show several tributary channels which trend south, but it cannot be determined from existing data if the channels also transect Long Island and continue south across the shelf to a possible intersect with the Block shelf channel.

The deep valley from the ancestral Quinnipac River that trends southwest from New Haven Harbor with a thalweg of -224 meters has been described by Haeni and Sanders (1974); the seismic records from this study show that it continues past Milford and Bridgeport to the north of Stratford Shoal, then changes to a more southerly orientation west of Stratford Shoal and probably connects with the -213-meter valley (described by Grim, Drake, and Heirtzler, 1970) underlying the north shore of Long Island at Stony Brook near Crane Neck (Fig. 11). The valley's southward continuation is not clearly defined, but Williams (1976) theorized that it connects with a buried channel present on the shelf 5.4 kilometers seaward of Moriches Inlet. The valley was certainly a major drainage channel before Pleistocene time, and its depth and width in the Sound rival the Hudson River fjord and make it by far the largest buried channel extension of the present rivers in Connecticut.

The last bedrock channel of major significance is the buried extension of the Connecticut River which trends southeast from the present mouth toward Orient Point on Long Island. Sparker profiles several kilometers seaward of the river mouth show that the channel has a broad and open base with a thalweg of -78 meters (which is remarkably shallow), suggesting that glacial scour was not as pervasive as in other parts of the Sound. The channel continues south under Orient Point where glacial erosion has produced thalwegs of -152 meters and the channel has been filled with Lake Flushing varve sediments (Fig. 7).

2. Surface and Subbottom Sediment Character and Distribution.

The lithologic character of the sedimentary deposits in Long Island Sound to the maximum core recovery depth of 5 meters was determined by both macroscopic and microscopic examination of samples from the 80 cores shown in Figure 13. Information on areas where cores were not taken was derived from extrapolation of the core data, using the CERC acoustic profiles, and from literature sources.

Based on these analyses the surface and subbottom sediments have been classified, primarily by grain-size texture using mean grain diameter and

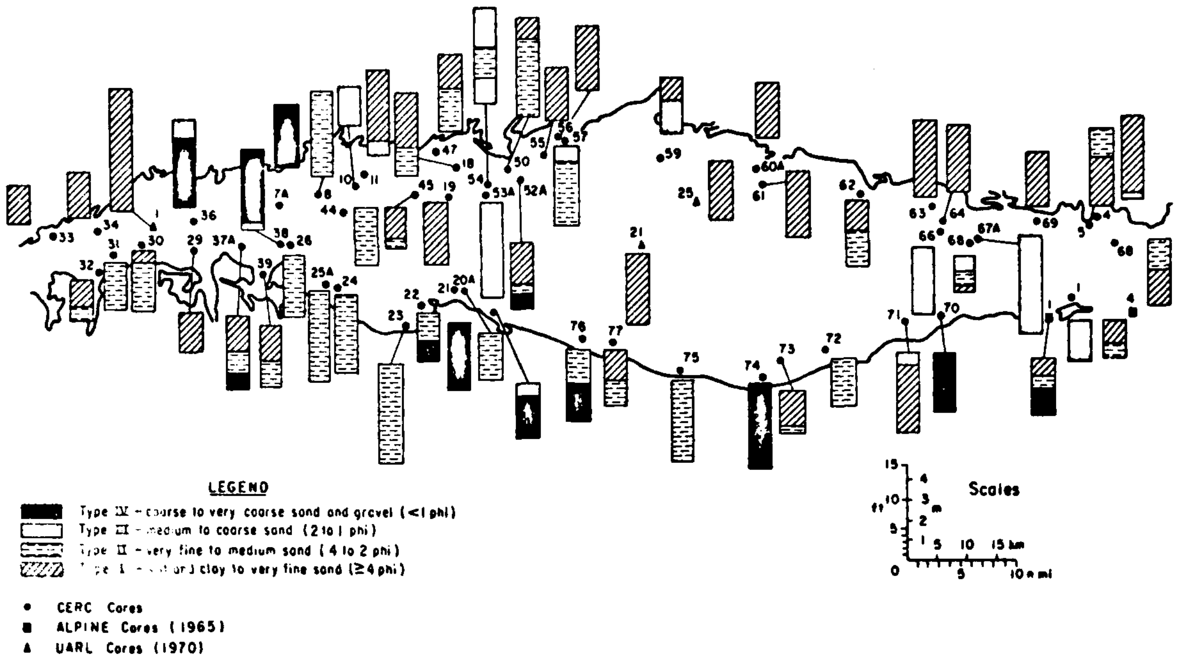

Figure 13. Eighty cores analyzed to show the four primary sediment types present in the top 5 meters of the sea floor.

sorting (Table 4), and by color of the dried sample, into four major sediment types: (a) type I sediments composed chiefly of clayey silts and very fine sandy silts (termed mud in some reports); (b) type II materials of very fine- to medium-grained sand, generally moderately to well sorted; (c) type III sediments of medium- to coarse-grained sand, moderately sorted, and (d) type IV lithology classified as coarse and very coarse sand and gravel, pebbles, and cobbles. The distribution of the major lithologies in the cores is shown in Figure 13; the surface distribution is shown in Figure 14.

a. Primary Sediment Classes.

(1) Sediment Type I. The sediments are composed of slightly cohesive and soft clayey silts and sandy silt with grain diameters smaller than 0.063 millimeter (>4 phi). Figure 14 shows that type I sediments are most abundant in the deeper parts of the Sound and along the Connecticut shore, except along parts of the coast where glacial sand and gravelly deposits are actively eroded by waves. Type I materials originate from rivers, primarily the Connecticut and Thames, that drain glaciated terrain to the north and have brought fine-grained sediment to the Sound for about the past 12,000 years. In addition to contributions of the rivers, Bokuniewicz, Gebert, and Gordon (1976) believe that significant amounts of fine-grained material are transported from Continental Shelf areas south of Long Island and are carried into the Sound and distributed westward by flood tidal currents. Cores 11, 13, 30, 32, 37A, 39, 45, 47, 50, 52A, 57, 59, 62, 73, and 77 show fine-grained sediment overlying sandy sediment, and patches of opaqueness on the acoustic profiles suggest that pockets of type I sediment with high gas content are common in deeper parts of the basins.

Table 4. Grain-size scales--soil classification (modified from U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977).

Unified Soils Classification	ASTM Mesh	mm Size	Phi Value	Wentworth Classification
COBBLE				BOULDER
		256.0	-8.0	
				COBBLE
		76.0	-6.25	
COARSE GRAVEL				
		64.0	-6.0	
				PEBBLE
		19.0	-4.25	
FINE GRAVEL				
	4	4.76	-2.25	
SAND coarse				
	5	4.0	-2.0	
				GRAVEL
	10	2.0	-1.0	
SAND medium				SAND very coarse
	18	1.0	0.0	
				SAND coarse
	25	0.5	1.0	
				SAND medium
	40	0.42	1.25	
SAND fine				
	60	0.25	2.0	
				SAND fine
	120	0.125	3.0	
				SAND very fine
	200	0.074	3.75	
SILT				
	230	0.062	4.0	
				SILT
		0.0039	8.0	
CLAY				CLAY
		0.0024	12.0	
				COLLOID

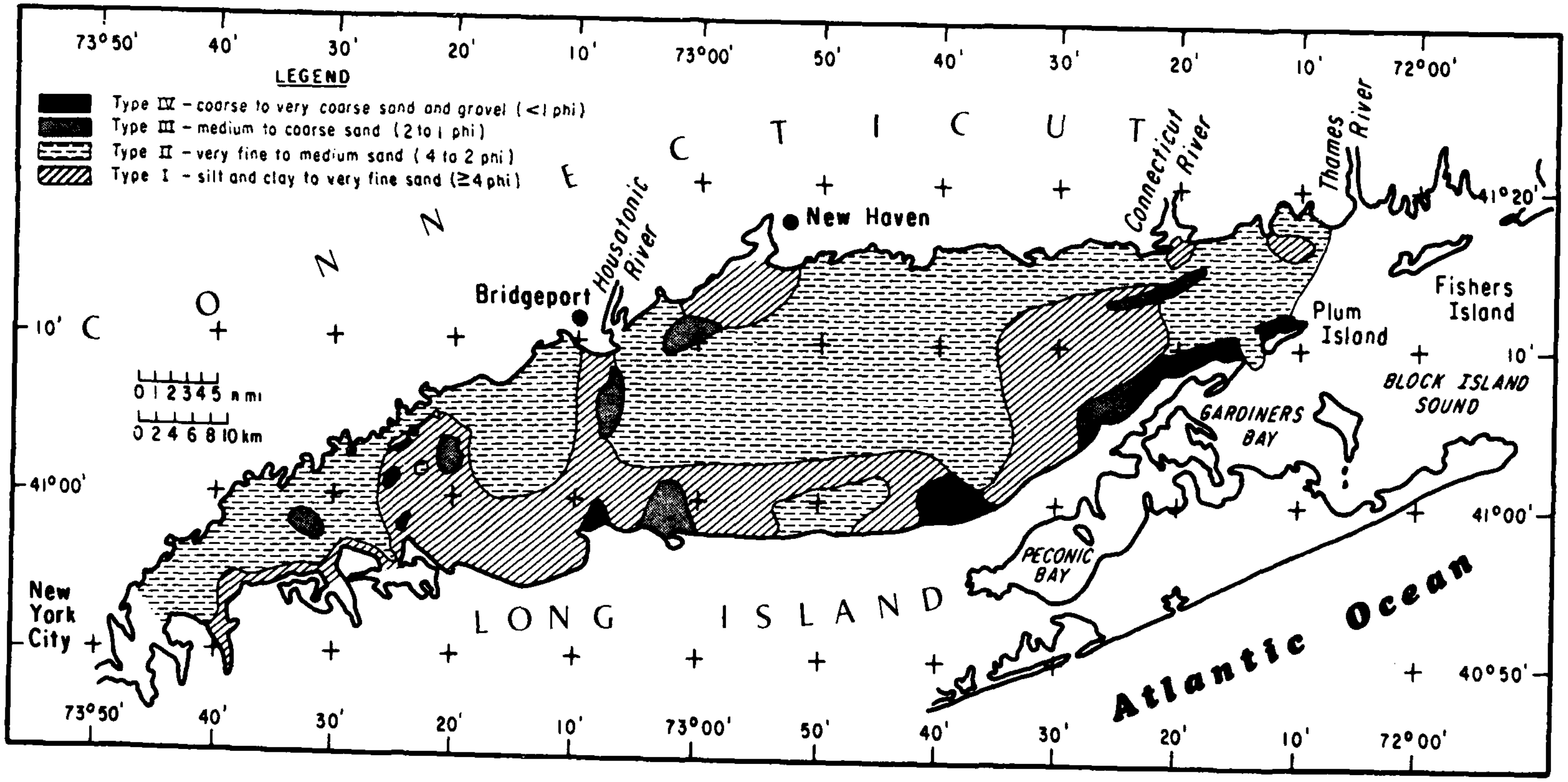

Figure 14. CERC cores and seismic profiles were used to map the surface sediment distribution of the four primary sediment types in Long Island Sound.

(2) Sediment Type II. These materials are very fine to medium grain-size sands from 0.125 to 0.5 millimeter (3 to 1 phi) primarily composed of quartz, feldspar, and rock fragments. These sands are most abundant along the Long Island coast where glacial sand outwash fans and the Harbor Hill Moraine are exposed to wave action and littoral processes (Fig. 14). Type II sands are also associated with the shoals and reef areas such as Cable and Anchor, Stratford, Middle Ground, Six Mile, and parts of Long Sand Shoal off the Connecticut River. In eastern parts of the Sound, sand waves with heights reaching 4.6 meters are present on the profiles. Bokuniewicz, Gordon, and Kastens (1977) studied the area and found that bed forms do not form where there is more than 10 percent mud or 12 percent coarse sand.

(3) Sediment Type III. These are medium to coarse sands in the size range from 0.5 to 1.0 millimeter (1 to 0 phi) with a composition similar to type II sediments except for higher percentages of rock fragments. The sediments are commonly associated with type II and IV sediments and are found along the shore and in patches adjacent to shoals where strong currents remove the finer sediments and leave the coarser sediments as lag deposits.

(4) Sediment Type IV. Materials with type IV sediments are coarse and very coarse sands and gravels larger than 1 millimeter (0 phi) in diameter, and are generally very poorly sorted. Because of the limiting diameter of the core barrel used in obtaining samples, the very coarsest materials in the cobble and boulder range are not represented; however, Ellis (1962), Flint and Gebert (1976), and Newman (1977) point out that boulders with diameters up to several meters are present in some of the glacial moraines and adjacent outwash heads. As with the other coarse-grained sediments, type IV materials are limited to nearshore and shoal areas where glacial deposits are exposed to wave attack or strong littoral or tidal currents.

Figure 13 shows that cores 7A, 21, 38, 70, and 74 contain several meters of type IV sediments that crop out on the surface, but cores 36, 22, 37A, 78, 52A, and Alpine 1 also show muds and finer grained sands overlying the very coarse material.

III. BEACH-FILL NEEDS AND RESOURCE POTENTIAL

1. Sandfill Requirements for Long Island and Connecticut Beaches.

The shoreline along the Atlantic coast from New Jersey to Cape Cod is probably the most heavily attended recreational area in the United States. The New York metropolitan area alone has more than 12 million people, and although most visit the Long Island south shore beaches there are a number of town beaches and public parks on the north shore that support recreation and periodically experience erosion problems where beach fill might provide a solution.

Connecticut has numerous resort communities along the coast, particularly between the New York-Connecticut border and New Haven, with parks and beach areas that experience frequent erosion and storm flooding. In the past 40 years many of these beach areas have had some form of coastal engineering work; the 15 areas shown in Figure 15 have or may in the future involve beach nourishment. Sherwood Park, and the coastal segment from Silver Beach to Cedar Beach south of Milford, are the regions most likely to require renourishment in the near future.

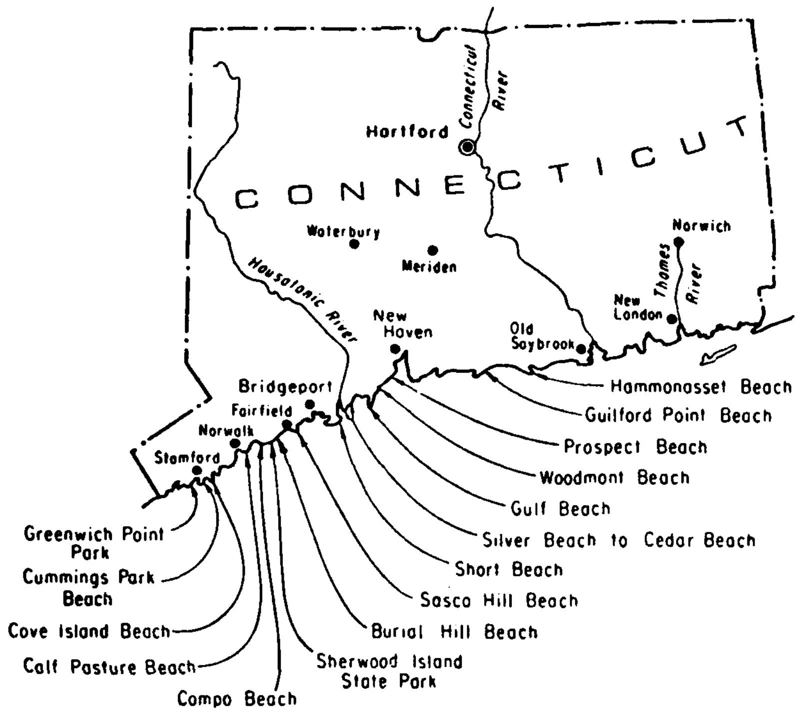

Figure 15. Projects along the Connecticut shore involving beach fill. All projects but Sherwood Park and Silver Beach to Cedar Beach are completed but may require future beach nourishment.

2. Suitability of Sand for Beach Nourishment.

Sand should meet certain important criteria for use as borrow material in beach restoration and protection projects. Factors to consider are the (a) population mean grain size and total size distribution, (b) mineralogic composition, (c) economics of sand recovery, and (d) placement and distribution on the beach. The borrow material should be of at least the same size and, preferably, slightly coarser than native material on the beach to be nourished. If borrow material was significantly smaller in particle size than indigenous sand it would be expected to be less stable and out of equilibrium with the wave and current regime. Consequently, it would be rapidly eroded and either carried offshore by wave-induced currents or transported parallel to the beach by longshore currents. In either case the net effect is accelerated retreat of the fill to readjust nearshore profiles, thus requiring considerably larger total volumes of initial fill and more frequent periodic replenishment. If the borrow sand does not have the same grain-size characteristics as the native beach sand, the grain-size population of the borrow sand should preferably be more poorly sorted; i.e., a greater variation in size classes than the native beach sand, and initial overfill relative to the required volume of fill for sand with the same characteristics as that of the native beach would be necessary for comparable performance.

Borrow material should be composed of hard, chemically and physically resistant minerals, such as quartz, which will not readily degrade in the high-energy nearshore-beach-dune environment.

The subject of beach fill and its design is covered in detail by Krumbein and James (1965), James (1974), Hobson (1977), and U.S. Army, Corps of Engineers, Coastal Engineering Research Center (1977).

3. Primary Sand and Gravel Deposits.

The seismic profiles and cores taken during this study reveal that 14 primary areas are present in Long Island Sound which contain relatively large quantities of sand and gravel that are accessible by conventional dredging methods. All areas in relation to the entire Sound are shown in Figure 16; the pertinent information for each deposit is included in Table 5.

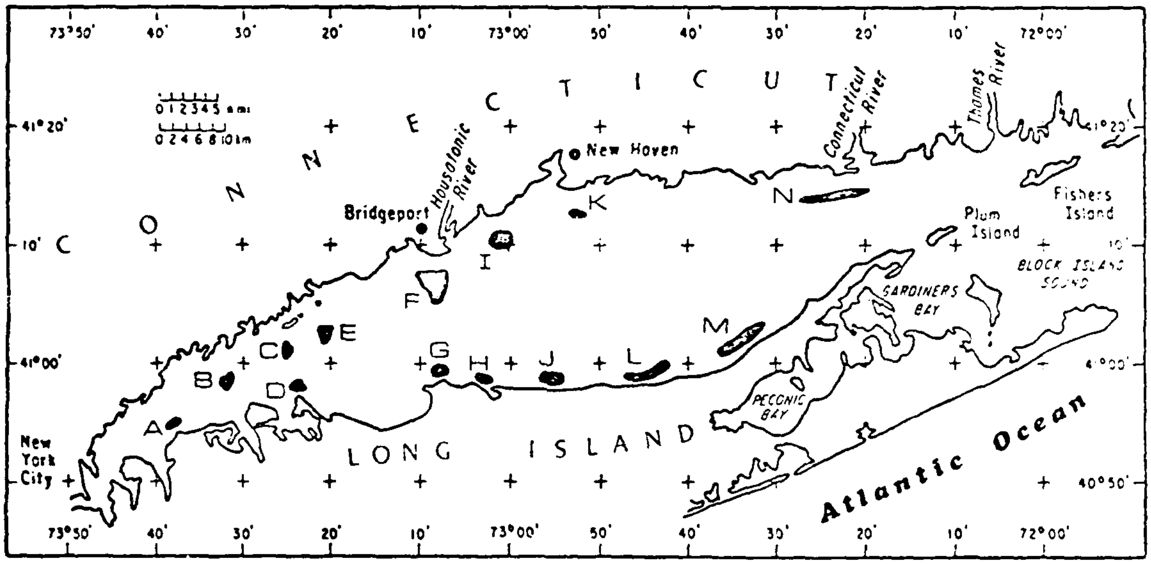

Figure 16. The 14 primary sand and gravel deposits identified in Long Island Sound.

The areal extent of each site is based on seismic data and bathymetric information; the thickness of each deposit was judged from the recovered sediment in the cores for each area. In many cases the seismic profiles show that sand in the deposits is considerably thicker than the amounts recovered in the cores, and that sand is also present in other parts of the Sound; however, the sand is either covered by various thicknesses of overburdens of modern fine-grained estuarine sediments, or is in water depths presently too deep for economic recovery. Therefore, a total volume of 189 million cubic meters of sand and gravel calculated for the entire Sound may be considered a conservative estimate and may be increased if additional long cores were used to explore the deposits in greater detail.

a. Area A - Matinicock Point Shoals. Area A consists of two irregular shoals inshore of the 15-meter depth contour to the northwest of Matinicock

Table 5. Characteristics of sand and gravel deposits.

Designation	Core No.	Water depths (m)	Thickness (m)	Mean grain size (mm)	Est. volume (million m^3)	Remarks
A	31	11 to 14	2.7	0.25 to 0.27	1	Deposit consists of two irregular ridges off Matinicock Point
B	36	8 to 18	4.3	0.60 to 0.90	6	Shoal about 6.4 km S. of Stamford is glacial till on a bedrock high
C	7A	7 to 18	3.1	0.50 to 1.20	4	Cable and Anchor Reef S. of Norwalk Islands is glacioflu-vial sediment on a bedrock high
D	26, 26B, 38	6 to 18	2.7	0.34 to 1.10	7	Shoal off Eatons Neck is composed of Pleistocene sands
E	9	12 to 20	3.9	0.28 to 0.62	4	Shoal about 5 km SE. of Norwalk Islands consists of steeply dipping forset strata
F	12 to 15, 49, 53A, 54	6 to 12	3.9	0.25 to 1.00	37	Shoal off Bridgeport is a glacio-fluvial delta with steeply dipping forset strata
G	21	6 to 15	3.3	0.61 to 0.89	5	Shoal off Crane Neck is composed of Pleistocene sands
H	78	6 to 15	2.7	0.31 to 1.10	5	Deposit consists of glaciofluvial sands
I	57	8 to 9	3.7	0.47 to 0.99	10	Shoal S. of Milford overlies the buried ancestral Quinnipiac River channel
J	76	6 to 17	3.5	0.43 to 0.48	7	Shoal is well stratified with forset strata
K	58A	6 to 9	2.1	------------[1]	3	Townshend Ledge is composed of glaciofluvial sediment on a bedrock high
L	75	6 to 18	3.8	0.40 to 0.65	40	Shoal has forset strata pro-grading west
M	72, 74	6 to 17	2.7	0.34 to 0.79	54	Shoal consists of Pleistocene glaciofluvial sands; sand waves with 5-m relief are present
N	64 to 67A	2 to 6	2.7	0.43 to 0.84	6	Long Sand Shoal is composed of stratified glaciofluvial and estuarine sands overlying bedrock

[1]Data unknown.

Point on the Long Island north shore (Fig. 17). The reduction of seismic line 1 shown in Figure 18 shows the morphology of the shoals and the undulatory character of the bedrock as well as the position of core 31 taken on top of the nearshore shoal. Core 31 contains almost entirely medium grain-size quartz sand. The character of the seismic profiles suggests that the shoals are composed of sandy material and probably have a similar origin. Using a sand thickness of 2.7 meters, the calculated sand volumes for the nearshore shoal and the offshore shoal are 642 and 367 thousand cubic meters, respectively. These volumes may be quite conservative as seismic line 1 (Fig. 18) shows that the nearshore shoal is a maximum of 6 meters thick, and that the offshore shoal is about 4.6 meters thick.

b. Area B. Area B is an isolated shoal (Fig. 17) situated immediately south of Stamford Harbor and to the west of a designated dumping ground for dredge material. The shoal rises to within 7.9 meters of the water surface but its base lies in water depths of about 21 meters on three sides and slightly more than 30.5 meters to the north. The seismic data suggest that the shoal is composed of sedimentary material perched on a bedrock high; core

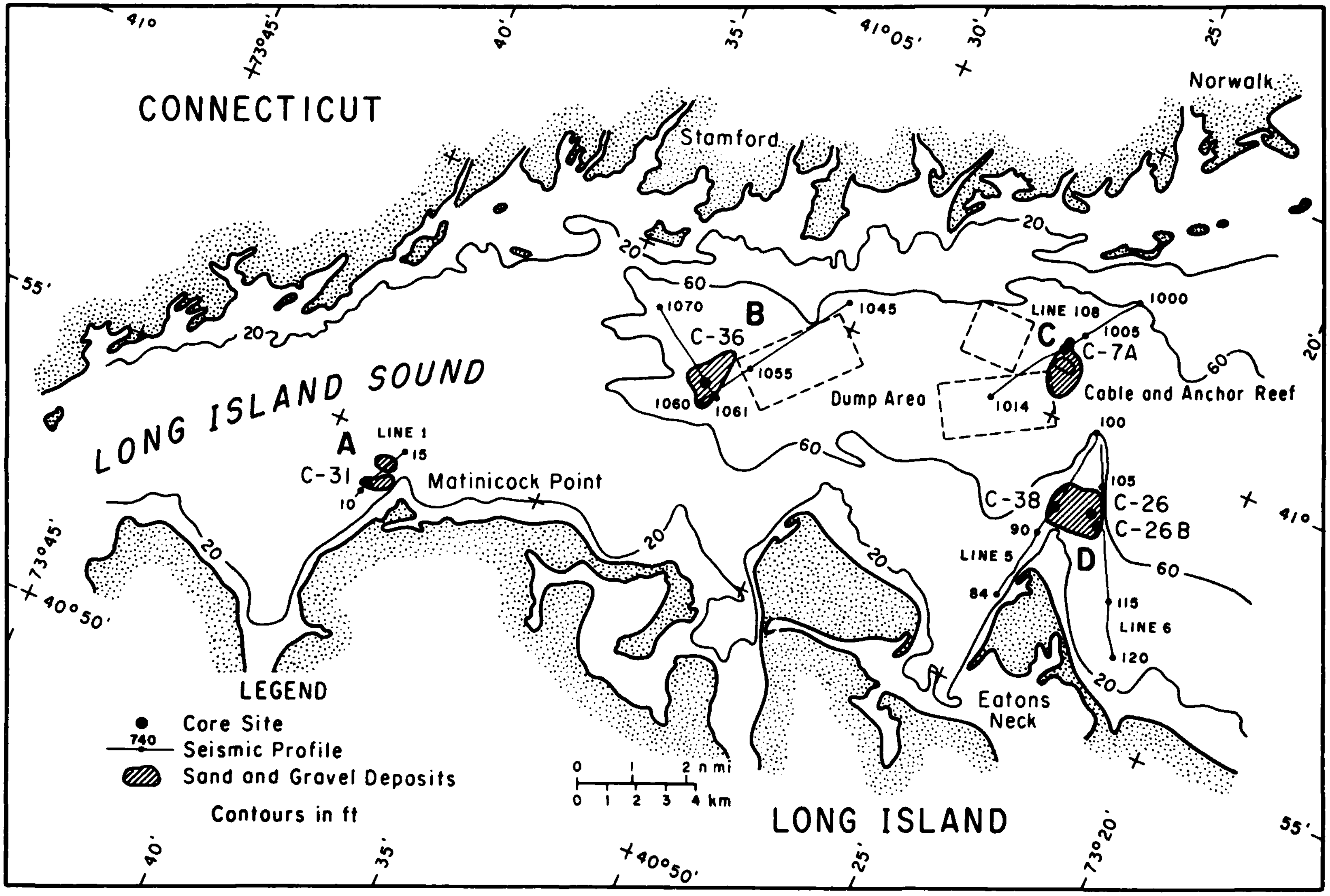

Figure 17. Map of western Long Island Sound showing four deposits and locations of the pertinent seismic and core data (contours in feet).

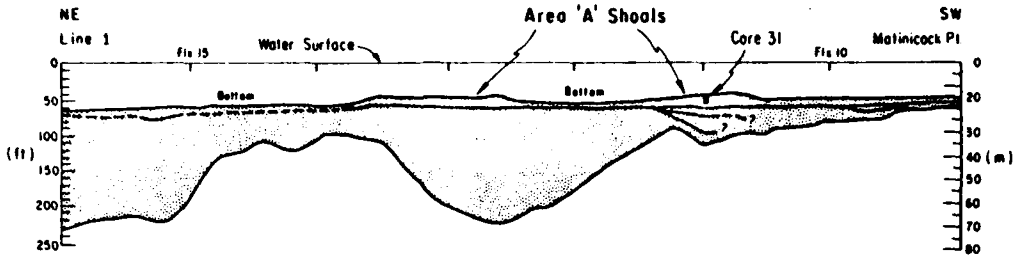

Figure 18. Interpreted profile of seismic line 1 of two shoals off Matinicock Point (see Fig. 17 for location).

36, taken on the shoal in 14.3 meters of water, contains 0.9 meter of silty medium and coarse sand overlying 3.4 meters of poorly sorted, very coarse sand and gravel. These data support the calculation that 6 million cubic meters of sand and gravel is available for area B. The disadvantages of this site are its distance of more than 7 kilometers from the Connecticut shore in the middle of the Sound, and its proximity to the dredged-material disposal area.

c. Area C - Cable and Anchor Reef. This area is the largest of several shoal features which trend in a north-south line from the Norwalk shore of Connecticut to Eatons Neck Point on Long Island (Fig. 17). Cable and Anchor Reef is in the middle of Long Island Sound surrounded by water depths of 21 to 34 meters, but it rises to within 6.7 meters of the water surface. Seismic profile line 108 shows the shoal is composed of steeply dipping forset-type sedimentary strata; core 7A taken in 17.7 meters of water in the northern end contains 3.1 meters of medium to coarse sand and gravel. Using a conservative thickness of 3.1 meters, the calculated sediment volume is 4 million cubic meters.

The disadvantages of using this site for extraction of sand and gravel are the same as for area B to the west, except that two designated dredged-material disposal areas are immediately west of area C and any dredging activity would have to be coordinated with uses of the disposal areas.

d. Area D - Eatons Neck Shoal. This site is part of a ridge extending north from Eatons Neck, Long Island, and apparently has a common origin with Cable and Anchor Reef (area C) to the north (Fig. 17). Both of these features probably relate to glaciofluvial depositional processes during the Pleistocene epoch. Area D is confined to water depths of 6 to 18 meters for practical purposes but its boundaries probably extend to the north at the apex of the -18-meter contour (Fig. 17). Seismic profile lines 5 and 6 show that the shoal is composed of forset-type strata; cores 26, 26B, and 38 show a composition of fine to medium sand on the east and medium and coarse sand and gravel in the west. These data were used to compute a volume of 7 million cubic meters for available sand and gravel within area D.

e. Area E. Area E is located almost 5.4 kilometers southeast of the Norwalk Islands and 9 kilometers south of Sherwood Point, and is bisected by the 18-meter depth contour (Fig. 19). As shown in Figure 20, the area is on the distal end of a southward-projecting ridge characterized by high-angle forset strata. The ridge has an average thickness of 6 meters and appears to be closely underlain by bedrock. Core 9 was taken on the northern part of the

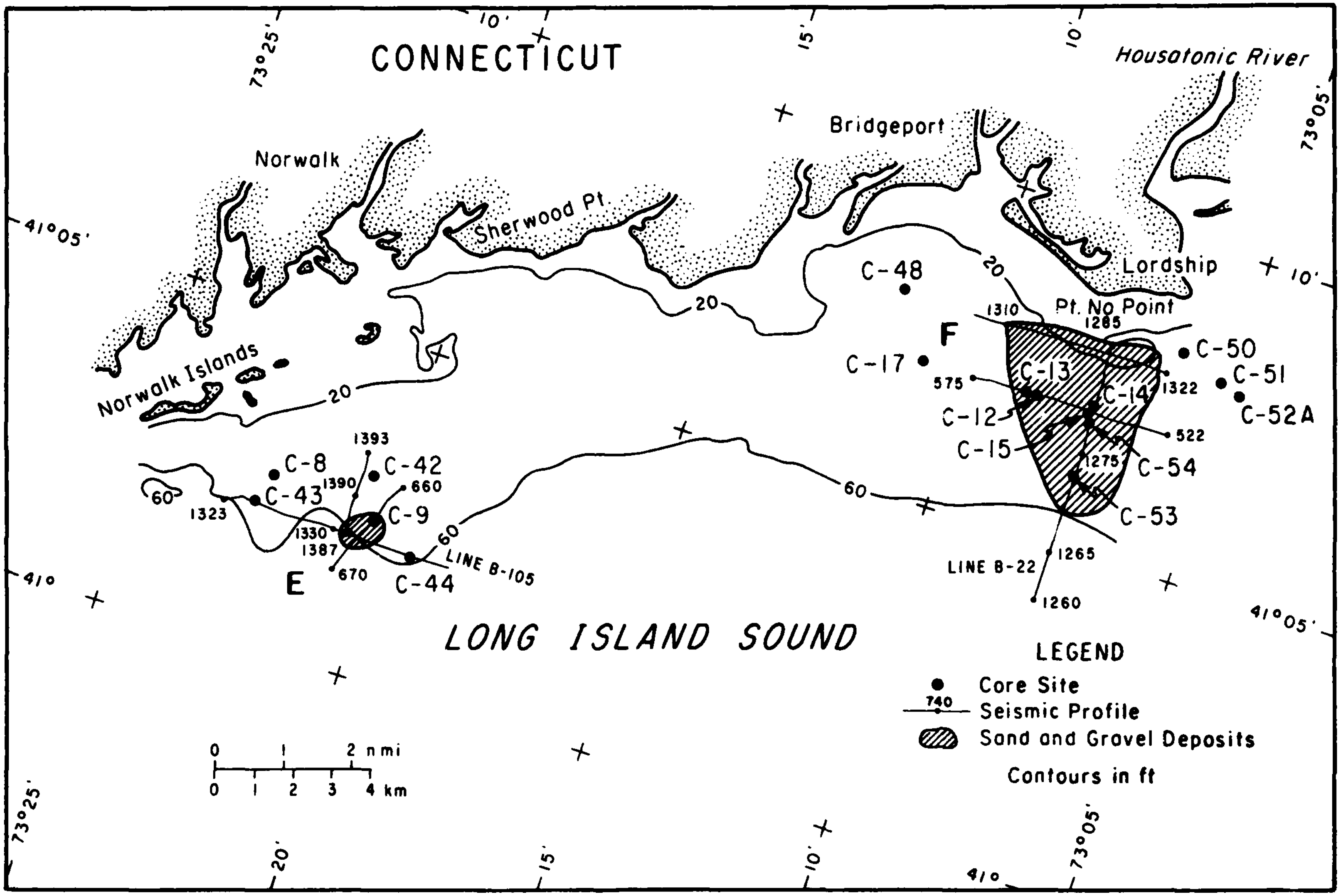

Figure 19. Map of primary deposits E and F along the Connecticut shore.

Figure 20. Interpreted profile of seismic line B-105 crossing area E southeast of the Norwalk Islands.

deposit and contains 1.2 meters of medium to coarse sand overlying 2.7 meters of clean, coarse sand and gravel with 0.6 meter of fine to medium sand at the base of the core. The volume of sand and gravel within the limits of area E is calculated to be 4 million cubic meters; however, cores 42 and 44 suggest that the deposit may be considerably larger and may extend to the north and east. Cores 8 and 43 to the west contain sediment that is considerably finer in grain size than core 9 and both have a higher silt and clay content.

f. Area F - Bridgeport Shoal. Area F is a triangular-shaped shoal about 7.2 kilometers southeast of Bridgeport at the mouth of the Housatonic River with its base at Lordship on the Connecticut shore, and its apex projecting southward about 5.4 kilometers into Long Island Sound (Fig. 19). The shoal appears to end abruptly at the 18.3-meter contour but a discontinuous extension may continue south at Stratford Shoal toward Crane Neck on Long Island. Water depths over the deposit range from about 6 to 18 meters. Data coverage consists of two east-west and one north-south seismic profiles as well as cores 12 to 15, 49, 53, and 54. These data show that the shoal is a highly stratified outwash delta that varies in thickness from 0 to 9.1 meters, with the southern one-third being the thickest (Fig. 21). This shoal appears to be the submerged and southerly extension of the Lordship outwash head described by Flint (1968). On land the outwash feature is composed of coarse-grained sediment with boulders as large as 1 meter. This sediment may also be present in area F, but none is obvious from the seismic data. The sand body probably originated as a glaciofluvial delta of the Housatonic River during a very late Wisconsin glacial advance in central Connecticut.

All seven cores in this area contain sand and only core 54 penetrated the sand body and recovered an underlying substratum of dark brown clay. Cores 17 and 48 to the west and cores 50, 51, and 52A to the east of the deposit show the shoal flanks are overlapped by muddy modern sediments which blanket adjacent bottom areas.

The sand contained in the outwash shoal is typically light brown, medium to coarse (0.25 to 1.00 millimeter; 2.0 to 0.0 phi) quartz sand with sparse shells and, locally, up to 15 percent small gravel. Since the sand is clean, generally free of fine particles, and is sufficiently variable in size characteristics from place to place, selective borrowing could be used to obtain desired size grading. Computations based on the seismic and core data show that the Bridgeport area has the highest potential of any of the deposits along the Connecticut shore of Long Island Sound. Using a thickness of 3.9 meters, the sand and gravel volume is 37 million cubic meters; however, the actual inplace volume may be more than twice this amount.

g. Area G. Area G, a circular deposit north of Old Field Point and Crane Neck on the Long Island northshore (Fig. 22), lies within the 6- to 15-meter contours and is defined by seismic profile line 11 and core 21. The seismic profile shows the area is underlain by horizontal sedimentary strata and core 21 contains a fairly uniform mixture of silty fine to very coarse sand with pebbles up to 6.4 centimeters in diameter. The deposit appears to have originated from Pleistocene glaciofluvial or glacial deposition processes and may be genetically related to the Bridgeport deposit (area F) and Stratford Shoal, both of which are alined to the north across the Sound. The limited data coverage in area G makes resource calculations inprecise but based on a thickness of 3.3 meters, the computed volume of sand present is 5 million cubic meters.

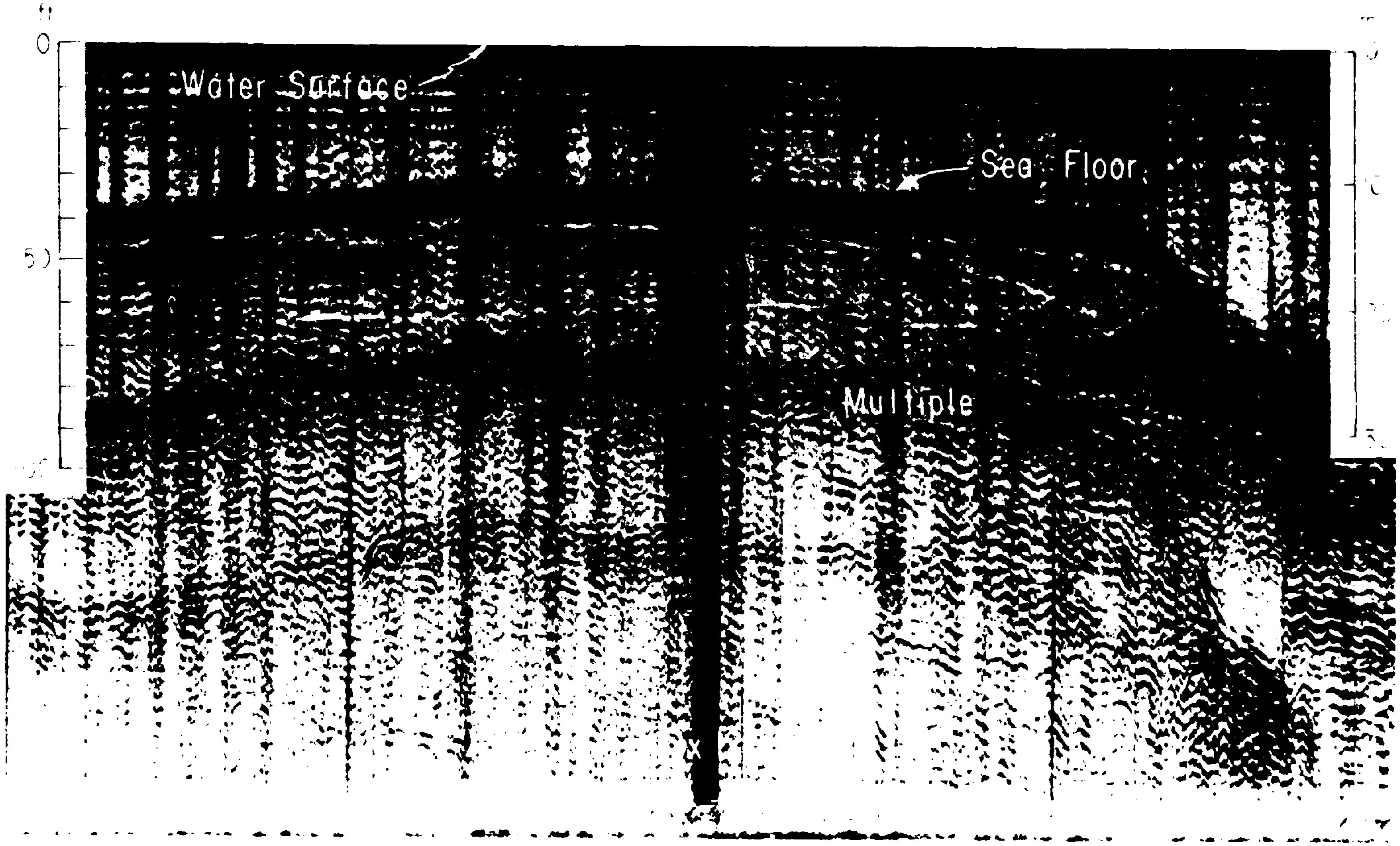

Figure 21. Interpreted profile of line B-22 at the south end of the Lordship outwash head (area F) showing forset stratification.

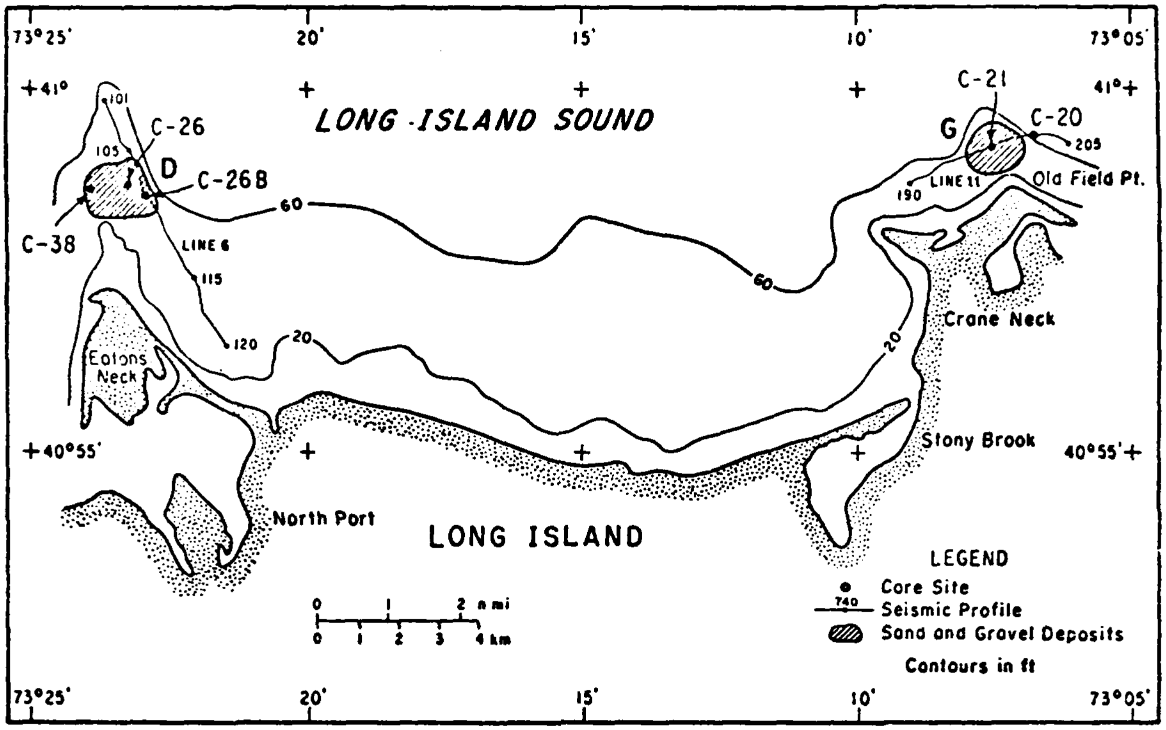

Figure 22. Map of sand and gravel deposits D and G along the north shore of Long Island.

h. Area H - Port Jefferson Shoal. The Port Jefferson deposit is on the north shore of Long Island 3.6 kilometers east of area G. Area H lies in water depths of 6 to 15 meters and, like area G, is defined by one seismic profile and core 78 (Fig. 23). Core 78 shows that the top 0.5 meter of the deposit consists of silty medium sand underlain by coarse sand to -1.8 meter, and that the base of the deposit to -2.7 meters is composed of brown, poorly sorted fine to very coarse sand and significant amounts of pebbles. The area H deposit is closely related to the adjacent Harbor Hill Moraine, and is possibly continuous with area G to the west as well as with areas J, L, and M to the east. Offshore, the sand and gravel of area H is overlapped by fine-grained sediments. The calculated volume of sand and gravel in the area is 5 million cubic meters based on a thickness of 2.7 meters.

i. Area I - Milford Shoal. Area I is situated about 1.8 kilometers off the Connecticut coast just south of the town of Milford and southwest of New Haven (Fig. 24). It comprises the southern part of a shoal which extends from about the -6-meter water depth close to shore to the -9-meter contour 2.7 kilometers offshore. Core 57 at the northern part of the shoal shows that it is composed of fine to very coarse sand. The periphery of the shoal is sharply defined and cores 55 and 56 to the southwest and northwest show the adjacent bottom is considerably finer in grain-size diameter. Using a thickness of 3.7 meters, the computed volume of sand and gravel in area I is 10 million cubic meters.

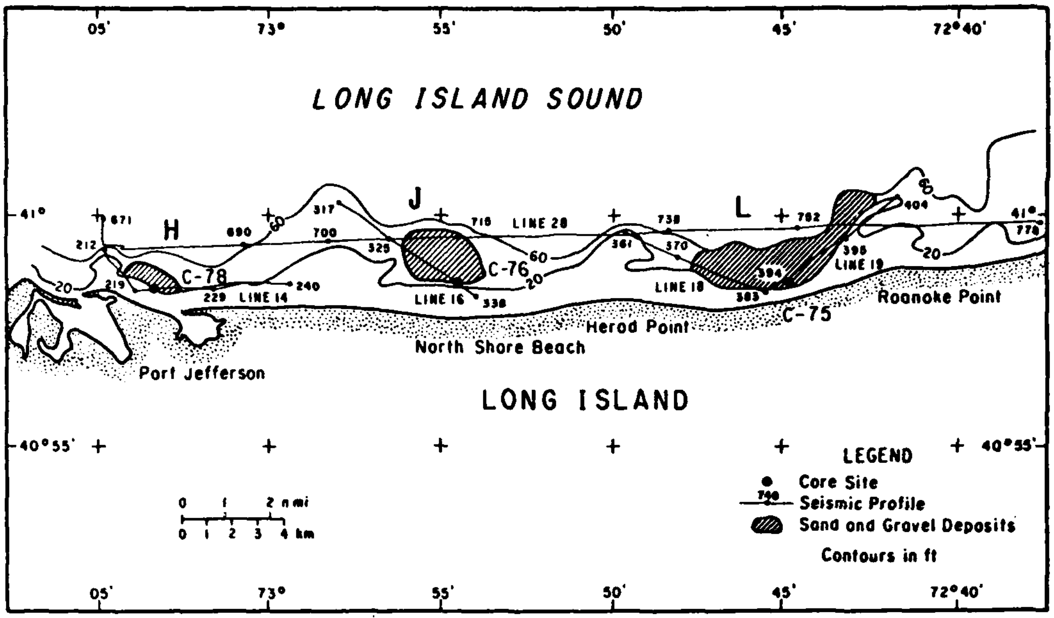

Figure 23. Map of the Long Island north shore from Port Jefferson to Roanoke Point showing potential borrow areas H, J, and L.

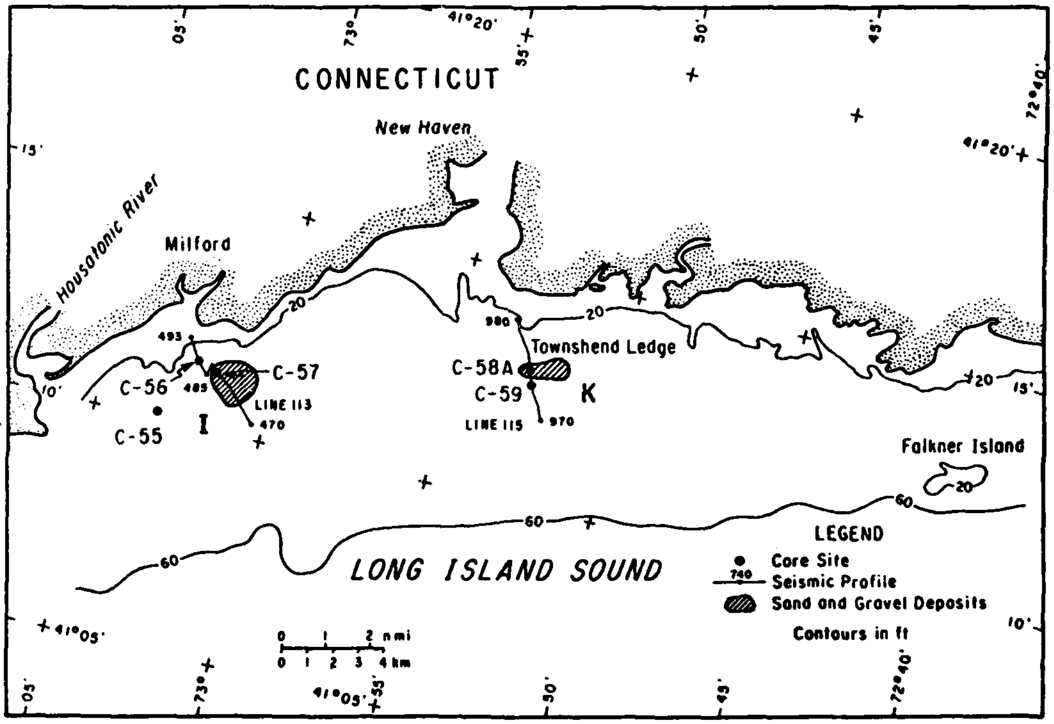

Figure 24. Map of deposits I and K near New Haven, Connecticut. Area I is the Milford outwash head and Townshend Ledge is a moraine remnant.

j. Area J. Area J, approximately 9 kilometers east of area H and immediately offshore of North Shore Beach, is defined by seismic lines 16 and 28 and core 76, and consists of an outwash shoal from the Harbor Hill Moraine. The surface of the shoal is characterized by several northeast-oriented ridges (Fig. 23) with relief up to 6 meters; seismic line 16 shows that the shoal is highly stratified with forset strata. Core 76 on the nearshore part of the deposit is composed of 1.7 meters of silty medium sand overlying 1.8 meters of medium to very coarse sand and small pebbles. The calculated sand volume within area J is 7 million cubic meters.

k. Area K - Townshend Ledge. This area is located about 2.7 kilometers south of the Connecticut coast and just east of the entrance navigation channel to New Haven (Fig. 24). Area K rises to within 5.5 meters of the water surface; the base is in about 10.4 meters of water to the north and up to 15.2 meters to the south. It is bisected by seismic profile 115, and core 58A was taken in -11.3 meters of water toward the western end. The seismic profile shows bedrock to be fairly high in the area but the ledge itself exhibits internal stratification. Core 58A shows that the strata consist of silty medium sand for the upper 0.5 meter and clean medium to coarse sand for the next 1.7 meter. Based on these data, the estimated volume of sand is 3 million cubic meters; however, this volume could actually be several times larger if the total relief for the entire ledge were considered.

Core 59 to the south of area K shows that gray, fine-grained modern sediment blankets the adjacent bottom and covers large quantities of sand and gravel that are probably contiguous with the sediments on Townshend Ledge. Core 59 shows 0.9 meter of silt overlying 1.7 meters of brown, clean, medium to coarse sand.

l. Area L - Roanoke Point Shoal. Area L is about 8 kilometers east from area J along the north shore of Long Island between the major headland shoals at Herod Point and Roanoke Point (Fig. 23). The area comprises the shoreface region beween the -6- and -18-meter contour and is transected by three seismic profiles; however, core 75 provides the only information on the actual physical character of the sediments in the deposit. Like the other deposits along the north shore of Long Island, area L is an outwash plain from the Harbor Hill Moraine to the south, but the presence of large bed forms on the bottom suggests that the surficial sediments are being actively modified by present-day estuarine tidal currents.

Core 75 was taken on the nearshore part of the deposit in 7 meters of water and contains 3.9 meters of fairly homogeneous, clean, fine to medium sand. The seismic profiles show that these sandy sediments are probably contiguous through the entire deposit. Seismic profile 28 offshore of the deposit shows that older fine-grained sediments are present from fixes 738 to 752, which probably represent glacial Lake Flushing lacustrine deposits.

Based on core 75, a sand thickness of 3.8 meters was extrapolated over the area to compute a total sand volume of 40 million cubic meters.

m. Area M. Area M, an elongate deposit more than 10.8 kilometers long and about 1.8 kilometers wide north of the town of Mattituck (Fig. 25), occupies the shoreface between the -3- and -18-meter contours; the presence of sand waves with relief up to 4.6 meters shows that the area is frequently

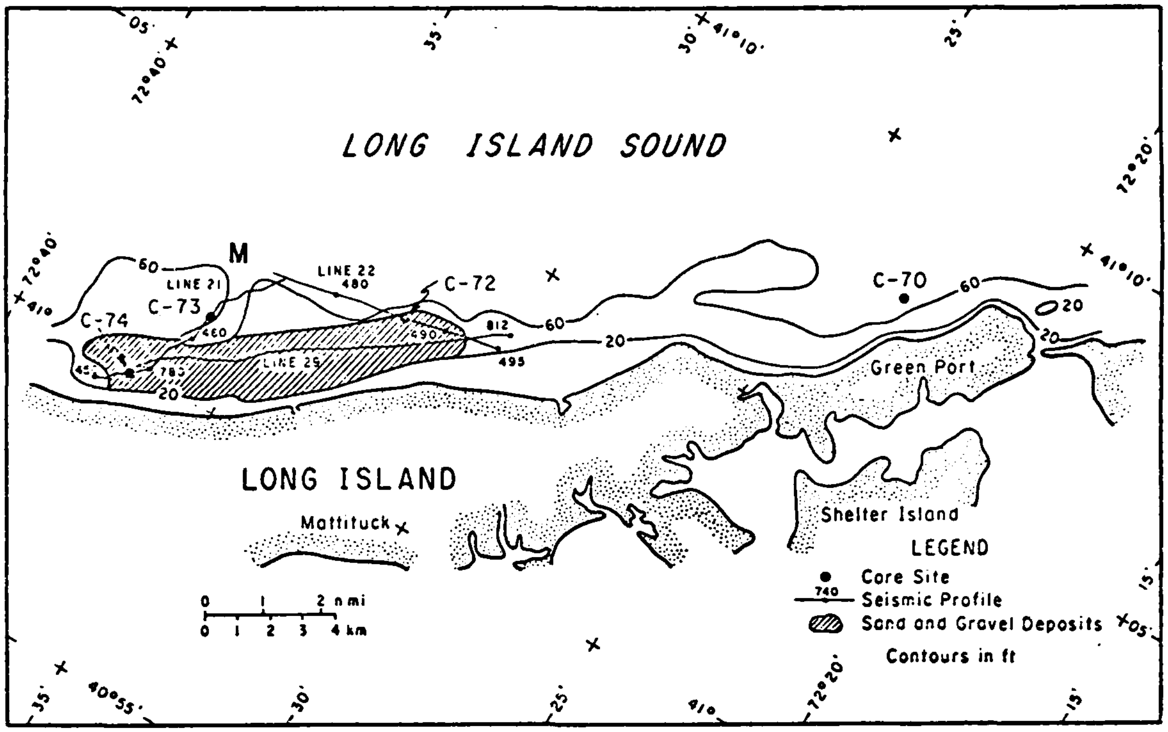

Figure 25. Map of borrow area M along the Long Island north shore.

subject to strong tidal surges. Seismic line 29 shows internal stratification in the deposit; core 74 to the west and core 72 on the eastern end contain 4 and 2.3 meters of clean, fine to coarse sand and pebbles, respectively. Seismic lines 21 and 22 show that the sand thins abruptly offshore and that flat-lying, fine-grained strata are present at -19.5 meters. Using a thickness of 2.7 meters, the deposit contains an estimated 54 million cubic meters of sand and gravel.

The seismic data and core 70 to the east of area M show that stratified sandy sediments continue well beyond the boundaries of area M; however, the -18-meter contour is very close to shore, hence the deposits are probably confined to a narrow band and removal of large quantities could adversely affect stability of the adjacent coast.

n. Area N - Long Sand Shoal. Long Sand Shoal, an elongate, slightly arcuate ridge about 3.5 kilometers off the mouth of the Connecticut River has a total length of 10.8 kilometers and a maximum width of less than about 450 meters, and tapers to the east and west. The minimum water depth over the shoal is 2.4 meters and the adjacent bottom to the north is on the order of 12.2 meters; the bottom drops abruptly to the south to depths of 45.7 meters within 1.8 kilometers of the shoal (Fig. 26).

There are several seismic profiles that run up to and adjacent to the shoal, but the extreme shallow water prevented the survey vessel from crossing the shoal. In addition, cores 64, 65, 66, and 67A taken on the shoal flanks provide good physical evidence of the subbottom character of the shoal.

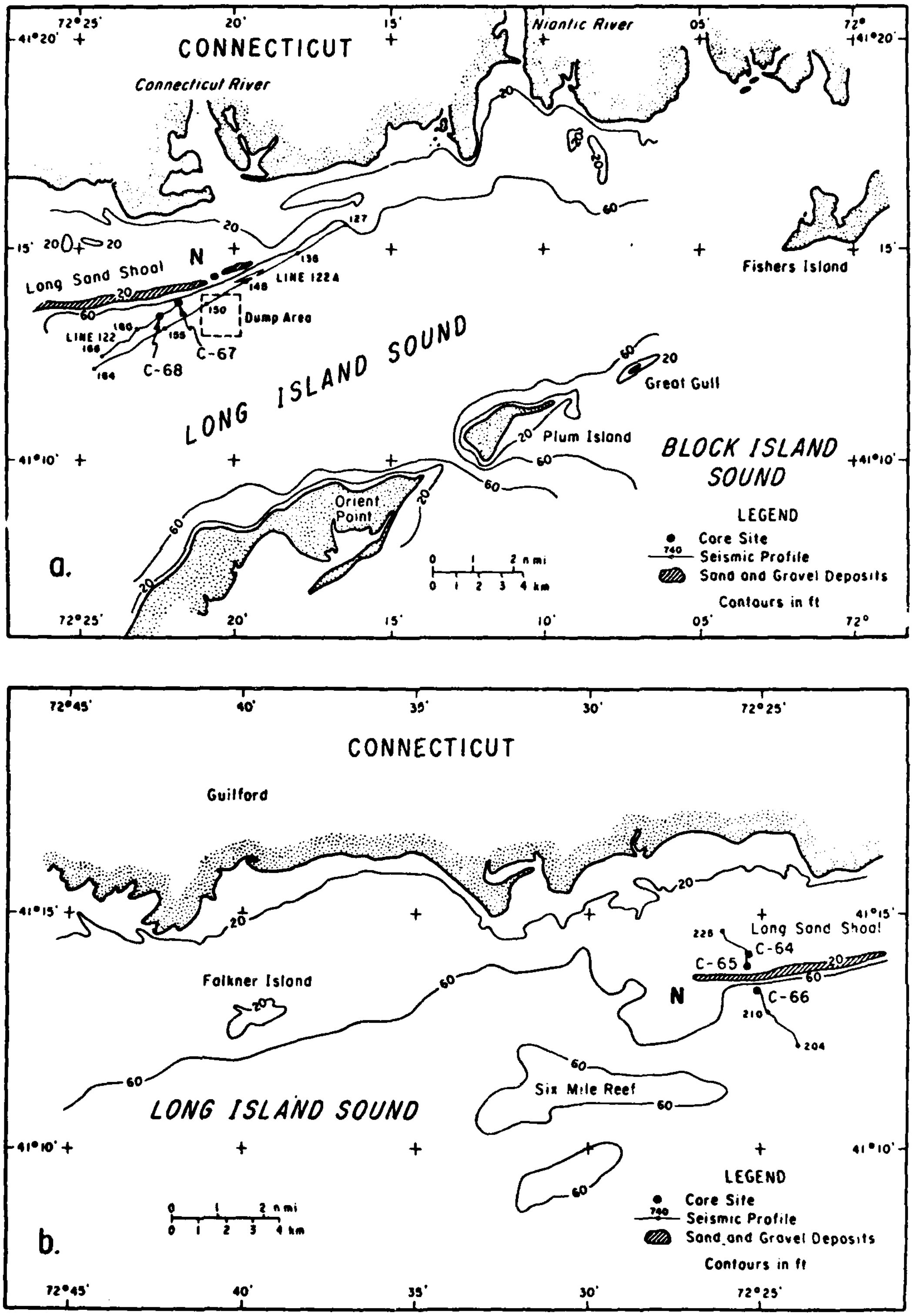

Figure 26. Map of eastern Long Island Sound showing the morphology of Long Sand Shoal.

Figure 27 shows that the bedrock surface in the vicinity of Long Sand Shoal is undulatory and has been deeply scoured by Pleistocene glaciers. The irregular bedrock surface has been filled and covered by flat-lying sedimentary strata which in turn are overlain by the almost horizontal strata comprising the shoal. Apparently, bedrock is about 11 meters beneath the shoal at fix 214; cores 66 and 67A show that the strata on top (which make up the shoal) are fairly uniform, fine and medium grain-size sands with thicknesses of 3.2 and 4.7 meters, respectively. Core 68, taken on the southern flank in 31 meters of water, shows that the sand pinches out and overlies older fine-grained sediments which probably are the horizontal strata filling the bedrock depressions shown in Figure 27. Cores 64 and 65 to the north of the shoal contain silty, very fine and fine-grained sediments which would be unsuitable for fill material.

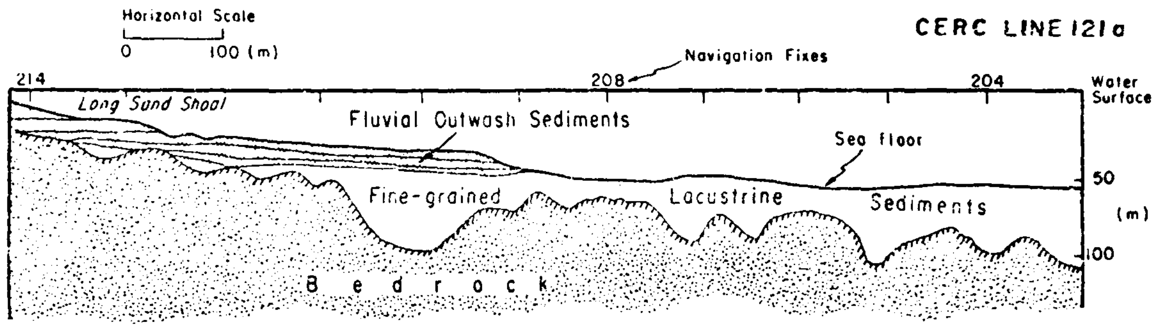

Figure 27. Interpreted profile of seismic line 121a over Long Sand Shoal. The Bedrock surface closely underlies the shoal which is characterized by highly stratified sandy sediments covering both bedrock and channel-filling fine-grained sediments.

Based on the limited seismic and core data available, Long Sand Shoal probably contains enough suitable sand to be designated a high potential deposit. Most of the largest grain-size sand is apparently concentrated along the main axis of the shoal or on the southern flank; the sediments on the northern flank are finer grained and have higher percentages of silt and clay. Using a thickness of 2.7 meters over the area shoaler than the -6-meter contour yields a total sand volume of 6 million cubic meters. Although Long Sand Shoal offers potential as a deposit, more densely spaced sediment samples are needed to reliably define its potential.

IV. SUMMARY

A detailed geological study was made of Long Island Sound using high-resolution seismic reflection profiles and long sedimentary cores to decipher the Quaternary geologic stratigraphy of the Sound and, in particular, to assess the sand and gravel resources.

Results from the study show that the deepest acoustic reflector is the bedrock surface which crops out on the Connecticut mainland and slopes south to depths of -250 meters at the north shore of Long Island. Bedrock is overlain in isolated areas by Cretaceous strata which have been deeply scoured by multiple glacial advances and long episodes of fluvial erosion. Pleistocene sediments are ubiquitous as thick accumulations of firm lacustrine silt and clay, as well as silty sands and gravels that were placed as discontinuous recessional moraine segments and outwash fans. Holocene sediments consist primarily of organic sandy muds that are accumulating in low-energy areas where tidal currents and wave action are minimal.

Fourteen shoal areas distributed around the Sound were found to offer the highest potential as sources of sand and gravel. Based on the seismic data and core results, these resources are conservatively calculated to be 189 million cubic meters in water depths less than 20 meters.

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APPENDIX A

CORE SEDIMENT DESCRIPTIONS

Appendix A contains visual descriptions of sediment from cores in the study area. Except where noted, sample locations are shown in Figure 2.

Visual descriptions for the CERC cores are based on both megascopic and microscopic examination. Sediment color is based on dry sample per Munsell Soil Color Charts (Munsell Color Company, Inc., Baltimore, Maryland, 1954 Edition).

Sediment names are based on the Wentworth size-scale as follows:

Sediment	Size (mm)	Phi
Gravel	>2	<-1
Very coarse sand	1.0 to 2.0	0 to -1
Coarse sand	0.5 to 1.0	1 to 0-
Medium sand	0.25 to 0.5	2 to 1-
Fine sand	0.125 to 0.25	3 to 2-
Very fine sand	0.0625 to 0.125	4 to 3-
Silt and mud	<0.0625	>4

Sorting terms[1]	Phi
Very well sorted	
	0.35
Well sorted	
	0.50
Moderately well sorted	
	0.80
Moderately sorted	
	1.40
Poorly sorted	
	2.00
Very poorly sorted	
	2.60
Extremely poorly sorted	

[1]Verbal sorting terms from Friedman (1962).

The contents of the core samples are tabulated in Table A-1.

Table A-1. Description of Alpine cores shown in Figure 13.[1]

Core No.	Depth (ft)	Description
		North Orient Point (water depth 48 ft)
1	0 to 1.0	Black mud
	1.0 to 2.5	Black silty sand
	2.5 to 4.5	Sand, medium grain, tan
	4.5 to 7.2	Gravel, fine-grained, mixed with about 10 pct sand
	7.2 to 9.0	Gravel, coarse 0.75- to 3-in pebbles
	9.0	Refusal
		East of Gull Light (water depth 44 ft)
4	0 to 0.5	Black mud
	0.5 to 3.5	Sandy silt, beige color
	3.5 to 6.0	Silty sand, fine-grained, closely packed
	6.0	Refusal

[1]From Alpine Geophysical Associates, Inc. (1965).

Table A-2. Sediment description from cores in Long Island Sound.

Core No.	Water depth (ft)	Internal (ft)	Description
1	61	0 to 6.3	Gray (2.5Y 6/2), moderately sorted, medium to course quartz sand
2A	56	0 to 2	Gray (5Y 6/1) medium sand, well sorted, with small pebbles
		2 to 2.5	(5Y 6/2), fine to medium sand
		2.5 to 4	(5Y 6/2), poorly sorted, fine to coarse sand
		4	Gray (5Y 7/1) silt
4	21	0 to 12.5	Gray (5Y 7/2) silt
		12.5 to 13.4	(5Y 8/2), clean medium to coarse sand
5	27	0 to 4.5	Gray (5Y 6/1) very fine sand
		4.5 to 12	Gray (5Y 7/2) silt
6B	55	0 to 4.5	Brown (2.5Y 6/2) fine sand
		4.5 to 10.5	Gray (5Y 7/2) silt
7A	58	0 to 0.5	Gray (5Y 6/2) medium sand
		0.5 to 10.2	(5Y 8/2), medium to coarse sand with ≤1.5-in-diam pebbles
8	50	0 to 13.8	Gray (5Y 6/2) micaceous well-sorted fine sand
9	50	0 to 4	(5Y 6/2) medium to coarse sand
		4 to 13	Clean, coarse sand with ≤1-in-diam pebbles
		13 to 15	Gray, (5Y 6/2) silty fine to medium sand
10	45	0 to 6	(5Y 7/3) clean, well-sorted, fine to medium sand
11	40	0 to 6	Gray (5Y 7/1) silt-clay
		6 to 10	(2.5Y 7/2), medium to coarse clean sand
		10 to 13.4	Light brown (5Y 7/2), very fine, fine micaceous sand
12	32	0 to 10.5	Gray (5Y 7/2) fine to medium sand
		10.5 to 13	Brown (7.5YR 5/6) medium sand
13	29	0 to 12.4	Grayish brown (5Y 6/1) fine to medium sand
14	31	0 to 4.5	Gray (5Y 6/2) fine sand
		4.5 to 12.2	Light brown medium sand
15	31	0 to 2	Gray (5Y 6/1), silty fine sand
		2 to 14.5	Gray (5Y 8/1), clean medium to coarse sand
16	38	0 to 8.5	Gray (5Y 7/1) silt
		8.5 to 13	Grayish brown (5Y 8/1), clean medium to coarse sand
17	31	0 to 9	Gray (5Y 7/2) silt
		9 to 12.5	Grayish brown (5Y 8/2) medium sand
18	32	0 to 8	Gray silt (5Y 7/2)
		8 to 13	Grayish brown (5Y 8/1) medium sand
19	54	0 to 10	Gray (5Y 7/2) silt
20A	82	0 to 6	Gray (5Y 6/2) very fine sand
		6 to 7	White (5Y 8/1) fine sand
		7 to 7.7	Pink (7.5YR 8/2) fine sand
21	41	0 to 10.7	Tan (10YR 7/3), silty, fine, medium to coarse sand with ≤2.5-in-diam pebbles

Table A-2. Sediment description from cores in Long Island Sound.--Continued

Core No.	Water depth (ft)	Internal (ft)	Description
22	53	0 to 4.5	Gray (5Y 7/1), silty fine sand
		4.5 to 7.8	Gray (5Y 8/2) coarse sand with ≤2-in-diam pebbles
		7.8	Gray (5Y 6/1) very fine sand and silt
23	51	0 to 16	Gray (5Y 7/1) fine to medium sand
24	54	0 to 12.5	Gray (5Y 8/2) very fine, fine to medium sand
25A	39	0 to 14.8	Light gray (5Y 8/2) fine sand
26	65	0 to 10.2	Reddish brown (10YR 7/4) fine sand
26B	67	0 to 9.5	Grayish brown (10YR 7/2) fine to medium sand
27	39	0 to 10	Gray (5Y 7/2) fine, clean sand
		10 to 15	Gray (10YR 7/3) silt-clay with ≤2-in-diam pebbles at 10 ft
29	39	0 to 6	Clay, grading in color from gray at top (5Y 7/1) to buff (2.5Y 8/4) at 2.5 ft to tan (10Y 7/6) at 6 ft
30	46	0 to 2	Gray clay (5Y 7/1)
		2 to 9.5	Brown (2.5Y 5/2), fine to medium clean sand with very small pebbles
31	36	0 to 7.8	Gray (5Y 6/2) fine to medium sand
32	37	0 to 4.5	Gray (5Y 7/1) silt-clay
		4.5 to 6.7	(10YR 7/2), clean fine to medium sand
33	20	0 to 6	Gray (5Y 7/2) silt-clay
34	61	0 to 7.2	Gray (5Y 7/2) silt-clay
36	47	0 to 3	Gray (5Y 6/1) slightly silty, medium to coarse sand
		3 to 14	Tan (10YR 6/3), clean poorly sorted very coarse sand with ≤1.3-in-diam pebbles
37A	52	0 to 5.5	Gray (5Y 6/2) silt-clay
		5.5 to 9	(10YR 7/3), clean fine to medium sand
		9 to 11.5	(10YR 7/4), clean coarse sand with small pebbles
38	39	0 to 12.8	Gray (10YR 8/1), clean medium to coarse sand with pebbles
		12.8	Gray (10YR 7/1) very fine silty sand
39	38	0 to 6	Gray (5Y 6/1) silt-clay
		6 to 10	Grayish brown (2.5Y 6/4), clean fine sand with small pebbles
41	65	0 to 4	Gray (5Y 7/1) silt-clay
		4 to 13.5	Gray (2.5 6/2) medium to coarse clean sand with small pebbles
42	37	0 to 1.5	Gray (5Y 5/2), silty coarse sand
		1.5 to 5	Gray (5Y 7/3) coarse to very coarse sand
		5 to 7	Gray (5Y 6/1) silty fine to medium sand
		7 to 9.2	Gray (5Y 5/3) slightly silty coarse sand with ≤2-in-diam pebbles
43	49	0 to 4	Gray (5Y 5/2), silty fine sand
		4 to 8.5	Gray (5Y 7/2), silty very fine sand
44	59	0 to 3.5	Gray (5Y 5/2), silty medium sand
		3.5 to 9.2	(10YR 8/2), clean medium sand
45	64	0 to 5.5	Gray (5Y 7/2), very silty fine sand
		5.5 to 6.5	Gray (2.5Y 8/2) fine to medium sand

Table A-2. Sediment description from cores in Long Island Sound.--Continued

Core No.	Water depth (ft)	Internal (ft)	Description
46	56	0 to 9.2	Gray (5Y 6/1) silty very fine sand
		9.2	Gray (2.5Y 7/2) fine sand
47	28	0 to 5.5	Gray (5Y 7/1) silt-clay
		5.5 to 12.3	Brown (2.5Y 8/4), micaceous fine sand
48	31	0 to 3	Gray (5Y 6/1) silt
		3 to 14	Brown (2.5Y 8/4) very fine to fine sand
49	25	0 to 7	Gray (5Y 6/1) medium to coarse clean sand
		7 to 9	Gray (5Y 7/1) very fine sand
		9 to 14.8	Brown (2.5Y 7/4) fine sand
50	36	0 to 3	Gray (5Y 6/2) silt
		3 to 15.8	Brown (2.5Y 8/2) clean medium sand
51	43	0 to 5.5	Gray (5Y 6/1) silt
		5.5 to 13.7	Brown (2.5Y 8/4) clean fine to medium sand
52A	43	0 to 7	Gray (5Y 7/1) silt
		7 to 8	Gray (2.5Y 7/2), fine to medium sand
		8 to 10.4	Brown (10YR 5/6), medium to coarse sand with very small pebbles
53A	32	0 to 15.5	Gray (5Y 6/1), clean medium to coarse sand fining with depth
54	24	0 to 6	Grayish brown (5Y 6/2), medium to coarse sand
		6 to 11	Gray (5Y 7/1), fine to medium sand
		11 to 14	Gray (5Y 6/1), clean medium to coarse sand
		14 to 15.2	Gray (5Y 6/1) silt
55	36	0 to 8.3	Gray (5Y 7/2) silt
56	28	0 to 10	Gray (5Y 7/2) silt, very fine sand
57	30	0 to 2	Gray (5Y 6/1), silty medium sand with granules
		2 to 12.2	Tan (5Y 8/3), clean fine to medium sand
58A	37	0 to 1.5	Gray (5Y 5/1), silty medium sand
		1.5 to 7	Gray (2.5Y 6/2), clean medium to coarse sand
59	48	0 to 3	Gray (5Y 6/1) silt
		3 to 8.5	Reddish brown (7.5YR 5.4), clean medium to coarse sand
60A	44	0 to 8.9	Gray (5Y 6/2) silt
61	45	0 to 10.3	Gray (5Y 6.2) silt
62	52	0 to 4.5	Gray (5Y 6/2) silt to very fine sand
		4.5 to 10.5	Gray (5Y 6/2), slightly silty fine to medium sand
63	37	0 to 12.5	Gray (5Y 6/2) shelly silt
64	53	0 to 7.5	Gray (5Y 5/2) silty fine sand
		7.5 to 11	Gray (5Y 7/2) silt
65	48	0 to 7	Gray (5Y 5/2) silty very fine sand
66	51	0 to 10.5	Gray (2.5Y 5/2), clean medium sand
67A	35	0 to 15.5	Gray (2.5Y 6/2) silty fine to medium sand with organic fragments

Table A-2. Sediment description from cores in Long Island Sound.--Continued

Core No.	Water depth (ft)	Internal (ft)	Description
68	101	0 to 2	Brown (2.5Y 5/2), clean medium to coarse sand
		2 to 4	Gray (5Y 6/2) silty fine sand
		4 to 5.6	Gray (5Y 7/2) silt
69	35	0 to 8.9	Gray (5Y 6/2) silt, organic material at top
70	34	0 to 9.5	Gray (5Y 6/2), slightly silty medium to very coarse sand with small pebbles
71	72	0 to 1.5	Brown (2.5Y 5/4) medium to coarse sand
		1.5 to 12.5	Gray (5Y 6/2) fine sand, fining downward to gray silt
72	47	0 to 2	Gray (2.5Y 6/2) fine to medium sand with broken shells and small pebbles
		2 to 7.5	Grayish white (2.5Y 8/2), clean fine to medium quartz sand
73	61	0 to 5.7	Gray (5Y 7/2) silt
		5.7 to 6.8	Grayish white (5Y 8/2), clean fine to medium sand
74	25	0 to 8	Light gray (5Y 7/2) medium to coarse sand with small quartz pebbles
		8 to 13.4	Brown (10YR 8/3) fine to coarse sand with small pebbles 8 to 11 ft, becoming fine with depth
75	23	0 to 12.7	Grayish white (5Y 8/2), very clean quartz, fine to medium sand
76	40	0 to 5.5	Gray (5Y 5/3) silty medium sand
		5.5 to 11.5	Gray (5Y 6/1) medium to very coarse sand with small pebbles
77	65	0 to 4.5	Gray (5Y 7/1) silt
		4.5 to 8.9	Light gray (5Y 7/2), clean medium sand
78	27	0 to 1.5	Gray (5Y 6/1) silty medium sand
		1.5 to 4	Gray (5Y 6/2) medium to very coarse sand
		4 to 6	Gray (5Y 6/2) coarse sand
		6 to 8.9	Brown (10YR 8/3), poorly sorted fine to very coarse sand with $\leq$1.25-in-diam pebbles

APPENDIX B

RESULTS OF GRAIN-SIZE ANALYSIS

This appendix provides a list of mean grain size and sorting for samples analyzed by sieving and settling-tube techniques. Sieve data were obtained by sieving samples at 0.5-phi intervals for periods of 20 to 30 minutes. Raw weights were used to calculate mean grain size and sorting by use of the method of moments.

Settling-tube data were obtained by analyzing samples on the CERC Rapid Sediment Analyzer (RSA). The RSA method records at the top and bottom of a 1-meter-long plastic tube as grains settle through the water column through use of two pressure transducers. Pressure data are digitized and converted to equivalent size data of spherical quartz grains, and mean grain size and sorting are computed by the method of moments. Through comparison of the results of samples analyzed by both the RSA and sieving techniques, empirical relationships were developed for converting data obtained on the RSA to its sieve equivalent. These expressions, given below, were used to convert RSA means and sorting values to their sieve equivalents.

$$\text{Mean:} \quad \bar{\phi}_{Sieve} = 0.1876 + 1.0735\ \bar{\phi}_{RSA}$$

$$\text{Sorting:} \quad S_{\phi_{Sieve}} = -0.146 + 1.453\ S_{\phi_{RSA}}$$

Conversion between phi units and millimeters for grain diameters is possible using the Wentworth grain-size scale (Table 4). The techniques are discussed in the Shore Protection Manual (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977) and Hobson (1979).

Table. Sieve mean grain size and sorting values for selected core samples.

Core No.	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)	Mean (mm)	Core No.	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)	Mean (mm)
5	0	2.19	0.88	0.22	13	-2	0.22	1.11	0.86
6B	0	1.23	0.96	0.43	13	-6	0.86	1.01	0.55
6B	-3	1.27	1.19	0.42	13	-8	1.97	0.40	0.26
6B	-4	0.41	0.85	0.75	13	-11	1.37	0.45	0.39
6B	-6	1.74	1.05	0.30	13	-13.4	1.04	0.58	0.49
7A	0	1.01	0.89	0.50	14	0	1.03	0.70	0.49
7A	-3	-0.30	0.79	1.23	14	-2	2.18	0.63	0.22
7A	-6	-0.19	0.75	1.14	14	-4	0.86	0.94	0.55
7A	-10	-0.20	0.92	1.15	14	-5	1.47	0.71	0.36
8	0	2.45	0.69	0.18	14	-6	0.39	0.64	0.76
8	-2	1.65	0.95	0.32	14	-9	0.98	0.45	0.51
8	-8	2.56	0.37	0.17	14	-12	1.55	0.75	0.34
8	-3.5	2.84	0.67	0.14	15	-3	2.00	0.47	0.25
9	0	1.23	0.80	0.43	15	-6	0.70	0.61	0.62
9	-2	1.34	0.91	0.40	15	-9	0.39	0.67	0.76
9	-3	1.29	1.07	0.41	15	-14.5	1.11	0.55	0.46
9	-7	0.97	1.31	0.51	16	-8	0.59	0.77	0.66
9	-12	0.69	0.99	0.62	16	-9	1.27	0.45	0.42
9	-15	1.82	0.98	0.28	16	-11	0.98	0.57	0.51
10	0	1.26	0.81	0.42	16	-12.8	0.88	0.56	0.54
10	-3	2.03	0.64	0.25	17	-9	0.38	0.77	0.77
10	-4	1.97	0.50	0.26	17	-11	1.25	0.45	0.42
10	-6	2.26	0.57	0.21	17	-12.5	1.12	0.40	0.46
10	-7	1.39	0.56	0.38	18	0	0.74	1.39	0.60
10	-13.3	0.83	0.68	0.56	18	-7	0.83	0.76	0.56
11	-1	0.24	1.35	0.85	18	-8	0.65	0.62	0.64
11	-6	-0.04	0.67	1.03	18	-8.5	0.91	0.58	0.53
11	-8	0.57	0.96	0.67	18	-13	1.09	0.67	0.47
11	-9	1.41	1.36	0.38	20A	-2	1.79	0.85	0.29
11	-13	2.54	0.86	0.17	20A	-2	1.96	0.56	0.26
12	0	1.81	0.80	0.29	20A	-5	1.33	0.99	0.40
12	-1	1.68	0.85	0.31	20A	-6	1.37	0.72	0.39
12	-4	0.95	0.57	0.52	20A	-7	1.39	0.60	0.38
12	-6	1.23	0.63	0.43	20A	-7.8	1.62	0.62	0.33
12	-7	1.64	0.60	0.32	21	0	1.97	0.89	0.26
12	-10	1.14	0.48	0.45	21	-1	1.75	0.61	0.30
12	-11	1.31	0.42	0.40	21	-2	0.90	0.78	0.54
12	-13	1.08	0.72	0.47	21	-8	0.69	0.74	0.62

Table. Sieve mean grain size and sorting values for selected core samples.--Continued

Core No.	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)	Mean (mm)	Core No.	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)	Mean (mm)
21	-10.8	0.54	0.75	0.69	30	-7.5	0.69	0.57	0.62
22	-7	0.77	0.94	0.59	36	-2.5	0.21	1.07	0.87
22	-10	0.16	0.51	0.90	36	-6	0.34	0.71	0.79
23	0	1.46	0.60	0.36	36	-8	0.19	0.80	0.88
23	-1	1.50	0.41	0.35	36	-14	0.69	0.95	0.62
23	-16	1.81	0.44	0.29	38	0	0.76	0.44	0.59
24	-3	1.48	0.73	0.36	38	-1	0.86	0.47	0.55
24	-6	1.16	0.56	0.45	38	-6	0.43	0.79	0.74
24	-8	1.32	0.54	0.40	38	-8	0.73	0.63	0.60
24	-12	2.09	0.70	0.24	38	-12.9	0.46	0.54	0.73
25A	0	1.18	0.48	0.44	39	-11	1.79	0.91	0.29
25A	0	1.34	0.33	0.40	41	0	0.38	0.80	0.77
25A	-2	1.48	0.37	0.36	41	-2	0.94	1.08	0.52
25A	-7	1.50	0.34	0.35	41	-6	0.75	0.73	0.60
25A	-9.5	1.53	0.39	0.35	41	-7	0.66	0.63	0.63
25A	-14.5	1.53	0.34	0.35	41	-13.3	1.26	0.66	0.42
26B	0	0.77	0.73	0.59	42	-1	0.53	0.46	0.69
26B	0	1.36	0.89	0.39	42	-3	1.05	1.64	0.48
26B	0	1.62	1.11	0.33	42	-6	0.17	0.71	0.89
26B	-1	1.70	0.61	0.31	42	-8	1.42	0.64	0.37
26B	-2	1.42	1.09	0.37	42	-9.5	1.37	0.64	0.39
26B	-2	2.16	0.89	0.22	43	-1.5	1.83	0.60	0.28
26B	-4	1.81	0.48	0.29	43	-2.5	2.53	0.81	0.17
26B	-5	1.64	0.34	0.32	43	-5	2.38	0.59	0.19
26B	-5	1.80	0.62	0.29	43	-8.5	2.70	0.74	0.15
26B	-7.4	2.10	0.54	0.23	44	-2	1.47	0.55	0.36
26B	-7.5	1.76	0.38	0.30	44	-3	0.84	0.86	0.56
26B	-10	1.97	0.51	0.26	44	-4	2.27	0.58	0.21
27	0	1.13	0.81	0.46	44	-5	2.24	0.59	0.21
27	-1	1.87	0.45	0.27	44	-6	1.15	0.81	0.45
27	-4	1.94	0.42	0.26	44	-9	0.93	0.55	0.53
27	-5.5	1.27	0.70	0.42	45	-6.5	1.54	0.59	0.34
27	-8	2.09	0.38	0.24	46	-7	2.03	0.67	0.25
27	-11.5	1.08	1.04	0.47	46	-8.7	2.35	0.67	0.20
28	0	0.75	0.63	0.60	47	-6	2.54	0.51	0.17
28	-1	0.68	0.47	0.62	47	-7	2.51	0.60	0.18
28	-2	0.77	0.42	0.59	47	-12	2.23	0.53	0.21
30	-4	0.87	0.58	0.55	48	0	0.77	1.08	0.59

Table. Sieve mean grain size and sorting values for selected core samples.--Continued

Core No.	Sediment depth (ft)	Mean (phi	Std. dev. (phi)	Mean (mm)	Core No.	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)	Mean (mm)
48	-5	2.06	0.75	0.24	57	-12	1.44	0.47	0.37
48	-10	2.79	0.51	0.15	62	0	-0.20	0.89	1.15
48	-14	2.12	0.67	0.23	62	-5	0.78	0.67	0.58
49	0	0.73	0.85	0.60	62	-10.5	2.03	0.79	0.25
50	-3	1.43	0.92	0.37	66	0	1.62	0.55	0.33
50	-4	1.88	0.48	0.27	66	-10.5	1.31	0.57	0.40
50	-10	1.33	0.62	0.40	67A	-13	1.29	0.76	0.41
50	-15.5	1.95	0.88	0.26	67A	-15	1.71	0.84	0.31
51	-4	-0.40	0.61	1.32	67A	-15.5	1.85	0.43	0.28
51	-5	1.25	0.50	0.42	68	0	1.01	0.20	0.00
51	-6	1.03	0.47	0.49	68	-2.5	2.72	0.67	0.15
51	-8	1.12	0.49	0.46	70	-4	0.34	0.67	0.79
52A	0	0.00	0.81	1.00	70	-6	0.24	0.78	0.85
52A	-5	-0.21	0.80	1.16	70	-7	0.31	0.69	0.81
52A	-6	1.41	0.75	0.38	70	-8.5	0.39	0.73	0.76
52A	-9.8	1.16	0.61	0.45	70	-9.5	0.28	0.58	0.82
53A	0	0.24	0.76	0.85	72	0	0.10	0.94	0.93
53A	0	0.39	0.71	0.76	72	-4	1.42	0.34	0.37
53A	-1	0.67	0.47	0.63	72	-7.5	1.22	0.51	0.43
53A	-2.5	0.71	0.93	0.61	73	-5	0.15	0.88	0.90
53A	-3.5	0.88	0.81	0.54	73	-6	1.40	0.67	0.38
53A	-5	0.85	0.48	0.56	73	-6.8	1.29	0.44	0.41
53A	-8	0.92	0.55	0.53	74	0	1.22	0.65	0.43
53A	-10	1.27	0.60	0.42	74	-7	1.02	0.79	0.49
53A	-10.5	0.98	0.64	0.51	74	-13.5	2.38	0.68	0.19
53A	-11	1.71	0.35	0.31	75	0	1.24	0.58	0.42
53A	-12	1.82	0.46	0.28	75	-7	0.94	0.65	0.52
53A	-13	2.16	0.48	0.22	75	-13.4	1.09	0.40	0.47
53A	-14	2.17	0.36	0.22	76	0	1.23	0.43	0.43
53A	-15.3	1.12	0.89	0.46	76	-5	0.65	0.48	0.64
54	0	0.76	0.58	0.59	77	-5	1.11	0.60	0.46
54	-3	0.94	0.61	0.53	77	-8	0.98	0.52	0.51
54	-4	0.79	0.69	0.58	77	-8.5	1.05	0.57	0.48
54	-5	1.31	0.55	0.40	78	0	-0.30	0.56	1.23
54	-6	1.45	0.70	0.37	78	-1	-0.48	0.31	1.40
54	-7	1.78	0.47	0.29	78	-3	0.70	0.65	0.62
54	-12	0.84	0.60	0.56	78	-5	0.79	1.07	0.58
57	0	0.49	0.99	0.71	78	-8.5	0.75	0.73	0.60
57	-6	1.85	0.63	0.28					

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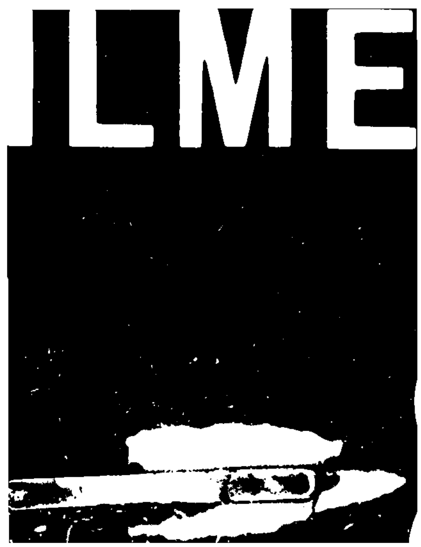
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